Wellington Regional Council

LIQUEFACTION HAZARD STUDY WELLINGTON REGION

STUDY AREA 3 - PORIRUA BASIN

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1 INTRODUCTION

The Wellington Region is among the most seismically active areas in New Zealand. Past earthquakes and studies have shown that there is a high risk of damage from earthquakes. There are also a number of areas within the region which are susceptible to earthquake induced liquefaction, and ground damage, which can significantly affect the infrastructure of the region.

The Wellington Regional Council (WRC) is developing a strategy aimed at achieving an acceptable level of risk from seismic and geological hazards in the Wellington Region. As part of this work, WRC is undertaking an assessment of the seismic hazard in the region, and the vulnerability of the community to the hazard. Works Consultancy Services Ltd (Consultancy Services) has been commissioned by WRC to undertake a liquefaction hazard study for the Wellington Region.

For the purpose of this study, the region has been divided into the following five study areas, the locations of which are shown on Figure 1 :

Study Area 1	Wellington City
Study Area 2	Hutt Valley
Study Area 3	Porirua Basin
Study Area 4	Kapiti Coast
Study Area 5	Wairarapa

Limited studies of the potential for liquefaction within the Wellington Region have been carried out in the past (Centre for Advanced Engineering, 1992 ; Institute of Geological and Nuclear Sciences, 1992 ; I R Brown Associates, 1991). The Centre for Advanced Engineering (1992) identifies the potential for liquefaction in parts of the Wellington Region, and I R Brown Associates (1991) identifies liquefaction susceptibility in the Lower Hutt. The IGNS (1992) report which formed stage 1 of this study, defines the concept of liquefaction, quoted recent New Zealand occurrences of liquefaction and recommended further work to assess the liquefaction hazard in the Wellington Region. These previous studies have generally been based on the regional geology, or are confined to limited areas or sites within the region.

The present study comprises a review of the historical records of liquefaction in the Wellington region (Works Consultancy Services, 1993a), and an assessment of the liquefaction potential and consequent ground damage in each of the five study areas. This report presents the liquefaction and ground damage assessment for Study Area 3, the Porirua Basin. The liquefaction assessments for Study Areas 1, 2, 4 and 5 are presented in separate accompanying reports (Works Consultancy Services, 1993b, 1993c, 1993d and 1993e).

This report presents a summary of the data compiled on the ground conditions of Porirua Basin, the results of limited site investigations carried out as part of this study, and the liquefaction and ground damage assessment for the Porirua Basin. It also includes maps of liquefaction susceptibility, potential, and ground damage, which present the results of the study.

2 THE STUDY AREA 3 - PORIRUA BASIN

2.1 Location

The Study Area 3, Porirua Basin is located to the north of Wellington City, extending from Glenside to Plimmerton, see Figure 1. It includes Porirua City, and the main suburban areas of Tawa, Linden, Kenepuru, Titahi Bay, Porirua East, Whitby, Paremata, Pauatahanui, Mana and Plimmerton. The NZMS 260 Map Grid Reference of the southern and northern ends of the area are R27 625 985 and R26 680 160 respectively.

2.2 Topography

The topography is dominated by the Porirua Harbour, north of Porirua City, and the Pauatahanui Inlet. Steep hillsides surround the harbour areas and the Tawa-Linden valley lies in the southern part of the study area.

2.3 Geology

The NZ Geological Map, 1 : 250,000, Sheet 12 Wellington (Department of Scientific and Industrial Research, 1967) shows the area to be Wellington Greywackes of Triassic age overlain by Holocene age sediments. The Wellington Greywackes comprise alternating dark grey argillite and sandstone. The Holocene age deposits which predominantly lie around the Porirua Harbour and Pauatahanui Inlet areas comprise undifferentiated alluvium in fluviatile, floodplain, estuarine and beach deposits, and dune sand. In addition to the natural geology of the area, reclamation fill materials also underlie some areas, particularly in the Porirua City.

A more detailed description of the geology of the Porirua Basin is given by the Department of Scientific and Industrial Research (DSIR, 1991a). The geology of the Pauatahanui area is not included in this report, but is presented by Dellow et al (1992). The surface geological map prepared by DSIR is presented in Figure 2.

3 COMPILATION OF DATA

Existing site investigations data has been compiled for the Porirua Basin from published reports, in-house records from past engineering projects and from information held by the Porirua City Council. A limited amount of data has also been accessed through private consultants and drilling contractors. A reasonable spread of data was gathered for the Porirua City area. However, a lack of information was identified in the Plimmerton, Mana and Titahi Bay areas where potentially liquefiable soils are considered to be present. Approval was obtained from the WRC for site investigations in these areas. Although there was a lack of data in the Pauatahanui area, no further investigations were carried out in view of the limited development in the area.

4 SITE INVESTIGATIONS

Site investigations comprising two boreholes and five Static Cone Penetration Tests were carried out between 6 and 11 January 1993, and were followed by laboratory classification tests on samples recovered during drilling. The boreholes were drilled to depths of about 10 m and 15 m, by Pendleton Corporation Limited. Standard Penetration Tests (SPT) were carried out in accordance with NZS 4402:1988 (Standards Association of New Zealand, 1988) during drilling, generally at 1 m depth intervals. Standpipes were also installed in the boreholes to confirm the groundwater levels in the area. The samples recovered were logged by an engineering geologist from Consultancy Services, who also supervised the work. The boreholes were drilled in the Plimmerton Domain in Plimmerton, and Kura Park in Titahi Bay. The locations of the boreholes are shown on Figure 3.

The Static Cone Penetration Tests (CPT) were carried out by Griffiths Drilling Co Ltd, under the direction of Consultancy Services. The tests were carried out in accordance with NZS 4402 : 1988 (Standards Association of New Zealand, 1988). The tests were carried out in Ngatitoa Domain in Mana, and the Titahi Bay Beach. Since the initial test at Ngatitoa Domain could not penetrate below a depth of about 2.8 m, a further two tests were carried out in the Domain area, and reached refusal at similar depths. An additional test was also carried out in the Titahi Bay Beach as the initial test met refusal at about 7 m, but again met refusal at a similar depth. The locations of the CPTs are shown in Figure 3.

Laboratory Tests comprising Atterberg Limits and Particle Size Distribution tests (wet sieving and hydrometer analyses for fine grained soils) were carried out by Consultancy Services' Central Laboratories. All the tests were carried out in accordance with NZS 4402 : 1986 (Standards Association of New Zealand, 1986).

The engineering geological logs of the boreholes, Static Cone Penetration Test results and the laboratory test results are included in Appendix A.

5 EARTHQUAKE SCENARIOS

5.1 The Scenarios

Two earthquake scenarios have been identified by the WRC for assessment of the potential for liquefaction and ground damage. These scenarios are :

Scenario 1

A large, distant, shallow (<60 km) earthquake that produces Modified Mercalli intensity of V-VI in bedrock over the Wellington Region. An example of such an event would be a magnitude 7 earthquake centred 100 km from the study area at a depth of 15 - 60 km, perhaps similar to the 1848 Marlborough earthquake. The return period of a Scenario 1 event is 20 - 80 years.

Scenario 2

A large earthquake centred on the Wellington - Hutt Valley segment of the Wellington Fault. Rupture of this fault segment is expected to be associated with a magnitude 7.5 earthquake at a depth less than 30 km. The mean recurrence interval for such an event is about 600 years, and the probability of it occurring in the next 30 years is estimated to be about 10%.

5.2 Ground Motion Parameters

The large, distant shallow Scenario 1 earthquake resulting in MM V-VI shaking on bedrock will be of sufficient duration, and contain sufficient low period energy to allow long-period response to develop at deep (or soft) sediment sites (DSIR, 1991b). This will result in a marked difference in the earthquake ground motions between rock sites and soft / deep soil sites. DSIR (1991b) have estimated the likely level of ground shaking for the various zones depending on the ground conditions, for each of the five study areas. The estimated ground motion parameters for the Porirua Basin are summarised in Table 1. As shown in the table, a Scenario 1 event is capable of producing a felt intensity of MM VIII-IX, and peak ground acceleration of up to 0.3 g, in zone 5 areas.

The large local Wellington Fault event (Scenario 2) will give a higher level of ground shaking throughout the region, but with smaller differences in average shaking between the different zones (DSIR, 1991b), in comparison to a Scenario 1 event. The distance from the source is also important for this earthquake scenario. For Porirua, the distance from the potential source, the Wellington Fault, is 6 km to 11 km. The major liquefiable areas, such as the Porirua City, are at a distance of about 10 km. The ground motions predicted in the Porirua

Basin by DSIR (1991b) are summarised in Table 1. The predicted felt intensity in a zone 5 area in Porirua is MM X-XI, and the peak ground acceleration for zone 5 is about 0.5 g to 0.8 g (DSIR, 1991b).

6 GROUND CONDITIONS

6.1 Sub-Areas

The Study Area 3, Porirua Basin, can be subdivided into areas based on their surface geology and topography as shown on the geological plan prepared by DSIR (1991b), see Figure 2. The following sub-areas within the Porirua Basin are underlain by soils which may have a potential for liquefaction during earthquake shaking:

- Plimmerton
- Mana
- Paremata
- Pauatahanui
- Titahi Bay and Titahi Bay Beach
- Porirua Harbour & City
- Tawa & Linden

A borehole in each of the areas has been chosen, based on the available information on the geology and geotechnical properties, to represent the ground conditions in each area. These boreholes are used for the assessment of the potential for liquefaction in Section 7. Given the large extent of the Porirua Harbour & City area and its' importance, six key boreholes have been chosen for this area across the city. Boreholes have been chosen in preference of Static Cone Penetration Tests, because borehole information is available in most of the areas enabling comparison and consistent liquefaction assessment.

The key boreholes are presented in Figure 4, and their summary logs are presented in Figure 5. The ground conditions in each area are briefly discussed below :

6.2 Plimmerton

One borehole was drilled in the Plimmerton Domain as part of the site investigations for this study, see Section 4, and this has been chosen as the key borehole for Plimmerton, see Figure 4. One further borehole log has been identified in this area.

The Plimmerton Domain borehole (PL1) extends to a depth of 15 m, and shows the ground conditions to comprise a sequence of very loose to loose silty sand, and soft to very soft clayey / sandy silt, see Figure 5. The Standard Penetration Test (SPT) 'N' values recorded range from 1 to 8. The groundwater level encountered was at a depth of 0.3 m below ground surface.

The other borehole in the area indicates the soils to be more fine grained clayey silt and silty clay, underlain by clayey gravel at a depth of 11.5 m.

6.3 Mana

The Static Cone Penetration Tests carried out in the Ngatitoa Domain in Mana only penetrated to a depth of 2.8 m, and hence did not provide much information. This indicates that dense gravels or weathered bedrock to be present close to the ground surface in part of the Mana area. The dense materials encountered may either be natural deposits or fill materials. A borehole log subsequently located for the Mana area confirms the presence of dense gravel and sand deposits close to the ground surface. However, boreholes drilled in the Mana Marina area indicate the presence of a sequence of sand or silty sand, which is loose near seabed level, and becoming denser with depth. SPT 'N' values range from under 5 near seabed level to over 50 at depth. It is possible that these sand deposits extend some distance onshore from the marina area, but its extent is not known. One of the boreholes on the Mana Marina has been used as the key borehole (MA1), see Figures 4 and 5.

6.4 Paremata

A number of boreholes have been located adjacent to the Paremata bridge across the entrance to the Pauatahanui Inlet. One of the boreholes has been used as the key borehole (PAR), see Figures 4 and 5. This borehole shows about 4 m of silty sandy gravel underlain by loose sand and sandy silt, and very dense gravelly sand. An inspection of the other boreholes in the area shows that the depth of the sediments in the area varies significantly with surface rock exposures in places. SPT 'N' values range from 4 to 21 in the sediments and over 50 in the underlying gravelly sand, see Figure 5.

The groundwater levels are expected to be high, near sea level, and are likely to fluctuate with tidal sea level variations.

6.5 Pauatahanui

Boreholes sunk for the Pauatahanui Bridge as well as in the inlet for an environmental study (DSIR, 1980) have been located. The environmental study borehole indicates very soft to firm silt, peaty silt and some sand to a depth of 13 m, overlying gravel. However, there are no geotechnical properties given for the holes. The Pauatahanui Bridge boreholes, one of which is chosen as the key borehole (PAU) for liquefaction assessment, show an interbedded sequence of silty sand, sandy silt, clayey silt and silty / sandy gravel to a depth of 11.5 m, underlain by bedrock, see Figures 4 and 5. SPT 'N' values range from 1 to 6 for the sand and silt, with values of 13 to over 50 for the gravel, see Figure 5.

The groundwater level is high at about 1 m to 2 m below surface.

6.6 Titahi Bay and Titahi Bay Beach

A borehole was drilled in Kura Park and two Static Cone Penetration Tests were carried out at the Titahi Bay beach, as part of this study.

The Static Cone Penetration Tests indicate the presence of sandy gravel with some clay/silt layers at the Titahi Bay Beach.

The Kura Park borehole has been chosen as the key borehole (TI1), and is shown in Figure 4. This borehole showed silty sand and sandy silt with some thin clayey silt layers to a depth of about 9 m, underlain by sandy gravel, see Figure 5. The SPT 'N' values in the silty sand ranges from about 8 to 26. The geological plan prepared by DSIR (1991a), shows the sand to be windblown sands, see Figure 2.

The groundwater level is high at 0.85 m below ground surface.

6.7 Porirua Harbour & City

This area comprising land surrounding the Porirua Harbour and the Porirua City is underlain by estuarine sediments, see Figure 2. Much of this area has been reclaimed by placing fill on the estuarine sand and silt. Boreholes for many structures in the area have been compiled. In view of the large extent of the area, six key boreholes have been chosen from this area, for consideration of liquefaction potential. These boreholes include two in the Elsdon area at the Porirua Technical Institute (PO1) and a warehouse site (PO2), one from the investigations for the Porirua Ramp Bridges replacement (PO3), two from the Porirua City Centre investigations (PO4 and PO5), and one from investigations for the Mungavin Interchange (PO6). The locations of these key boreholes are shown on Figure 4, and their summary logs are presented on Figure 5.

The boreholes identified above show that the surface fill material is generally loose to medium dense silty and sandy gravel, and is about 2 m to 4 m thick. The fill is underlain by estuarine sand and silt of varying thickness and composition. Some of the silt layers are indicated to be organic. In general the sand, silty sand and sandy silt have been found to be loose to medium dense, and become more clayey and gravelly at the southern end of Porirua City, near the Mungavin Bridge. The borehole results are summarised on Figure 5.

The groundwater levels are generally high in the area, and lie at a depth of about 1.5 m to 3 m below ground surface.

6.8 Tawa and Linden

The geological map (DSIR, 1991a) shows the ground conditions in the Tawa and Linden areas to be alluvial gravel, see Figure 2. The limited amount of investigation information in the Tawa and Linden areas appear to confirm this. These investigation results show the presence of silty clays and silty and clayey gravel. Some boreholes show small thicknesses of silty sand, and it is possible that such layers of small thickness and limited lateral extent do exist, particularly adjacent to the streams in the area. In view of the limited potential for liquefaction in this area, key boreholes have not been presented, and assessed. No information is available on the groundwater levels, but they are likely to be variable, with higher levels near streams.

7 LIQUEFACTION ASSESSMENT

7.1 Introduction

Liquefaction includes all *"phenomena giving rise to a loss of shearing resistance or to the development of excessive strains as a result of transient or repeated disturbance of saturated cohesionless soils"* (National Research Council, 1985). Earthquake induced liquefaction of soils is caused by ground shaking, giving rise to an increase in the porewater pressure in loose, mainly cohesionless soils. Where the increasing porewater pressures cannot dissipate rapidly, and become equal to the overburden stress, the soil liquefies, and loses most of its shear strength. This state is known as "initial liquefaction" or a peak cyclic pore pressure ratio of 100 %. The soil is then said to have "liquefied". A comprehensive definition of the terms associated with liquefaction is given by the American Society for Civil Engineers (1978), and is reproduced in Appendix B. They define liquefaction as *"the act or process of transforming cohesionless soils from a solid state to a liquefied state as a consequence of increased pore pressure and reduced effective stress"*.

Although soils may develop initial liquefaction, their subsequent behaviour will depend on their density and soil characteristics. Many soils may develop a state of initial liquefaction but may only have limited strain potential.

Liquefaction most commonly occurs in loose sands and silty sands, but is also found to occur in loose sandy gravels and low plasticity sandy silts and silts. Soft cohesive soils such as clays and silty clays do not strictly undergo liquefaction, but could nevertheless suffer similar consequences such as lateral spreading, flow slides or failure of structures due to a significant loss of undrained shear strength as result of strong ground shaking.

7.2 Methodology for Assessment of Liquefaction

The following methodology has been used to assess the potential for liquefaction in the Porirua Basin :

1. Identification of areas vulnerable to liquefaction based on the geology, and selection of key boreholes for the assessment of liquefaction potential ;

2. Assessment of the liquefaction susceptibility of soils based on the soil descriptions and the particle size distributions ;

3. Assessment of liquefaction potential, considering different appropriate methods based on the available information. The methods by

Ambraseys (1988) and Seed and Idriss (1982) have been used, where Standard Penetration Test results are available.

4. The potential for ground damage has been evaluated based on the assessed potential for liquefaction, the thicknesses of layers, geometry and topography, see Section 8.

5. Consideration of past earthquake events and any observed liquefaction and ground damage to confirm assessment.

7.3 Identification of Areas Vulnerable to Liquefaction

Considering the geology, and the ground conditions discussed in Section 6, the areas vulnerable to liquefaction have been identified. As discussed in Section 6, key boreholes have also been identified for each of the areas, for further assessment of liquefaction potential. The Tawa and Linden area is not considered vulnerable in general, because of the limited thicknesses of any sand or silt layers identified. The areas identified as vulnerable to liquefaction, together with the key borehole(s) in each area are presented below :

Sub-Area	Key Borehole(s)
Plimmerton	PL1
Mana	MA1
Paremata	PAR
Pauatahanui	PAU
Titahi Bay and Titahi Bay Beach	TI1
Porirua Harbour and City	PO1, PO2, PO3, PO4, PO5, PO6

The locations of the key boreholes are shown on Figure 4, and the summary logs of these boreholes are presented in Figure 5.

7.4 Liquefaction Susceptibility Based on Particle Size Distribution

The soils which are susceptible to liquefaction have been identified based on the description of the soils in key boreholes, and particle size distribution analyses, where available.

The particle size distribution curves available for soil layers in the key boreholes are shown on Figure 6, together with their depths. The particle size distribution curve envelopes for "easily" and "very easily" liquefiable soils, as presented by Tsuchida (1971), are also superimposed on the chart for comparison. The comparison shows that the majority of the soils identified are susceptible to liquefaction. Exceptions are some soils in the Plimmerton area (PL1, 10 m) which have an excessive amount of fines, or some layers in Porirua City (PO5, 6.1 m) which contain a significant amount of gravel.

Generally, loose to medium dense sand and silty sand have been identified as susceptible to liquefaction, and those loose sands with more than 35 % fines (low plasticity sandy silts or silts) or more than 35 % gravel (sandy gravels) have been identified as possibly susceptible. For this purpose, "fines" is defined as the percentage of soil fraction having a grain size of less than 63 µm.

7.5 Assessment of Liquefaction Potential

The soils in the areas considered to be susceptible to liquefaction were assessed using established liquefaction evaluation procedures. The potential for liquefaction was evaluated for the two earthquake scenarios discussed in Section 5, using the information from the key boreholes.

7.5.1 Ambraseys' Method

Ambraseys (1988) has developed a simple chart for the assessment of liquefaction based on the distance from the epicentre or the peak ground acceleration, the magnitude of the earthquake, the corrected Standard Penetration Test (SPT) value, and the groundwater level, see Figure 7. For the given two scenarios, knowing that the groundwater levels are generally only 1.5 m to 3 m below ground level, the corrected SPT values below which liquefaction occurs can be determined as shown in Figure 7.

The figure shows that for a Scenario 1 earthquake,

(a) soils in the ground shaking zone 2, with corrected SPT values of below about 8 to 14 are likely to liquefy ;

(b) soils in the ground shaking zones 3 to 5, with corrected SPT values of below about 15 to 22 are likely to liquefy.

For a Scenario 2 earthquake originating from the Wellington Fault, soils with corrected SPT values below about 22 to 35 are likely to liquefy.

The corrected SPT values of the soils susceptible to liquefaction in the Porirua Basin area are about 1 to 25. Therefore, the soils in the Porirua area have a potential for liquefaction.

7.5.2 Seed and Idriss Method

A more detailed assessment of the potential for liquefaction of susceptible layers of soils can be carried out by the most widely used method proposed by Seed and Idriss (1982) and described by the National Research Council (1985). This method takes into consideration the peak ground accelerations, the magnitude of the earthquake (which also allows for the effect of duration of shaking), the effective overburden stress, and the groundwater levels. The cyclic stress ratio caused by a given earthquake scenario can be calculated and together with the corrected SPT value plotted on the graph of Cyclic Stress Ratio vs Corrected SPT value, see Figures 8 and 9. Empirical correlations have allowed Seed and Idriss (1982) to develop curves for different magnitude earthquakes and soil fines content, which separate the liquefiable and liquefaction resistant soils. If the calculated point falls within the range for liquefiable soils, then the soils are said to have a potential for liquefaction. Depending on the distance of the plotted point from the curve, the margin of resistance to liquefaction can be judged.

The curves for the two earthquake scenarios are shown on Figures 8 and 9, together with the points calculated for the layer in each key borehole with the most susceptibility to liquefaction. The graph shows that the majority of these critical layers have a potential for liquefaction in both earthquake Scenarios 1 and 2.

7.5.3 Liquefaction Assessment using Static Cone Penetration Tests

The potential for liquefaction can also been assessed using the results of Static Cone Penetration Tests, which provide a continuous record of the cone and friction sleeve resistance. The soil type may be interpreted from the CPT results. However, they are often used in conjunction with a limited number of boreholes, from which the fines content of the soil can be determined. Since, only a limited number of CPTs were available in the Porirua Basin area and because they were not available for all the sub-areas, boreholes have been used in preference to CPTs. However, DSIR (1990) have carried out some CPT and Seismic CPTs in the area, and assessed the soils to be potentially liquefiable.

7.6 Historical Evidence

There is limited historical records of liquefaction in the Porirua. There is a passing remark of liquefaction in the Porirua Basin by Commander Drury in 1855 (Works Consultancy Services, 1993a), which said:

"I am informed the Porirua road is sunk in places".

As discussed in the historical study report (Works Consultancy Services, 1993a), it is considered likely that the sinking of the road is the consequence of liquefaction.

The absence of any other reports of liquefaction in the Porirua Area is considered to be a reflection of the absence of human settlement in Porirua, at the time of the large earthquakes affecting the Wellington Region.

7.7 Discussion

Based on the evaluation using different methods presented in Section 7.5 above, the potential for liquefaction of the soils have been assessed. Figures 8 and 9 show that there is a potential for liquefaction during a Scenario 1 earthquake, in most locations assessed, except Titahi Bay. At Titahi Bay, the soils have a marginal resistance against liquefaction. At two locations in the Porirua City, Elsdon and Mungavin, the soils have a marginal potential for liquefaction, see Figure 8.

During a Scenario 2 Earthquake, a magnitude 7.5 event on the Wellington Fault, there is a high potential for liquefaction of all susceptible soil layers considered, see Figure 9.

Table 2 shows a summary of the liquefaction assessments for the most critical soil layers in the key boreholes.

8 LIQUEFACTION INDUCED GROUND DAMAGE

8.1 Introduction

The likely mode and order of ground damage has been assessed for the two earthquake scenarios based on available literature and engineering judgement. The actual ground damage will depend on the ground conditions and topography at each site and should be assessed based on actual ground conditions. The assessment made in this section merely provides an indication of the type and order of magnitude of ground damage.

In view of the uncertainties, where appropriate, simple rules have been formed based on engineering judgement and have been applied to provide a consistent assessment over the whole region.

The main types of ground damage due to liquefaction are subsidence, slope failure of sloping ground, and lateral spreading of banks and embankments built on liquefiable ground.

The presence of a surface layer, which is resistant to liquefaction, above layers susceptible to liquefaction will minimise any liquefaction induced ground damage at the surface. In the Porirua City Area, there is generally a 2 m to 4 m thick layer of fill which is resistant to liquefaction. However, based on the chart proposed by Ishihara (1985), it is assessed that liquefaction induced ground damage would still occur given the high peak ground accelerations of 0.6 g to 0.8 g predicted for Scenario 2. The level of damage may be limited for a Scenario 1 event depending on the thickness of the liquefiable layer and the actual peak ground acceleration experienced.

However, where lateral instability is likely, the presence of a surface layer will not necessarily preclude ground damage.

8.2 Ground Subsidence

The approximate likely magnitude of liquefaction induced ground subsidence has been estimated for the key boreholes, based on the thickness of soils likely to liquefy, and the earthquake scenario. The assessment has been based on the method proposed by Tokimatsu and Seed (1987), which includes a chart for an earthquake of Richter magnitude 7.5. The estimated subsidence is therefore somewhat conservative for the Scenario 1 event. The subsidence is presented to the nearest 50 mm in Table 3.

8.3 Slope Failures

Most of the areas susceptible to liquefaction in the Porirua Basin are located adjacent to the coastline, Porirua Stream/Porirua Harbour or the Pauatahanui Inlet. The areas are generally flat, but their ground slopes are not known in detail. However, since most of the areas lie adjacent to stream, harbour or coastal banks, the potential for lateral spreading overides any slope failure considerations. The potential for lateral spreading of the banks is discussed in Section 8.4 below.

8.4 Lateral Spreading

Lateral spreading is likely to affect areas adjacent to the stream banks, harbour or coastal areas. Any embankments or abutments built on liquefiable materials are also likely to be affected.

For the purposes of this study, the following simple rules have been formed for preparation of the ground damage maps.

1. Areas within 50 m of stream and harbour banks are affected by lateral spreading, following a Scenario 1 earthquake.

2. Areas within 200 m of stream and harbour banks are affected by lateral spreading, following a Scenario 2 earthquake.

Embankments constructed on liquefiable ground can also undergo lateral spreading. However, this will depend on the construction details, and on what ground improvement measures were carried out during construction. Therefore, the ground damage for embankments and other earth structures have not been assessed.

8.5 Behaviour of Fine Grained Soils

Some areas of fine grained soils are present in the Porirua Basin Study Area, such as in Plimmerton. While fine grained soils are generally considered resistant to liquefaction, the ground damage observations during the 1855 Wairarapa Earthquake indicate that fine grained soils can liquefy, as discussed in the Wellington City Study Area Report (Works Consultancy Services, 1993b).

Even when liquefaction of soft fine grained soils does not occur, these soft soils can undergo loss of strength during severe ground shaking (as preciated for a Scenario 2 event), and can result in ground strains, and lateral spreading or instability of sloping ground similar to the ground damage experienced due to classic liquefaction.

9 LIQUEFACTION HAZARD MAPS

9.1 Liquefaction Susceptibility Map

The areas of the Porirua Basin which are susceptible to liquefaction have been interpreted using the surface geological map prepared by (DSIR, 1991a) and the type of soils reported in borehole information found during the study. This geological map does not cover part of the Porirua Basin Study Area, north of Plimmerton. Based on the general topography of the area, the presence of Taupo Swamp and the ground conditions at Plimmerton, the area north of Plimmerton, between the SH1 and the NIMT railway line is identified as susceptible to liquefaction. The areas susceptible to liquefaction are shown on Figure 10. This however does not imply that all the areas shown will liquefy during a given earthquake event. It is also possible that localised areas outside that shown on the map may liquefy during earthquake events.

9.2 Liquefaction Potential Map

The potential for liquefaction during the two earthquake scenarios considered in this study are shown on the map on Figure 11. This is based on surface geological map (DSIR, 1991a), the assessed ground shaking (DSIR, 1991b), the liquefaction assessment presented in Section 7, and a review of historical records of liquefaction (Works Consultancy Services, 1993a). The potential for liquefaction in the Porirua Basin Study Area has been classified into the following zones as shown on the liquefaction potential map on Figure 11:

- High potential for liquefaction. Liquefaction during both Scenarios 1 and 2.

- Moderate potential for liquefaction. Liquefaction unlikely or marginal during Scenario 1.

- Variable potential for liquefaction. Liquefaction potential varies at different locations from low to high. This zone covers areas where the available information suggests soils with a variable potential for liquefaction or soils unlikely to liquefy, at different locations within the same area.

- Low potential for liquefaction. Liquefaction may occur during Scenario 2. This zone includes areas where the soils are considered to be susceptible, but may or may not liquefy because of their density, fines content or gravel content.

As discussed in Section 9.1 above, the area north of Plimmerton, between SH1 and the NIMT railway is identified as having a low potential for liquefaction based on the minimal information available for this area.

9.3 Liquefaction Induced Ground Damage Map

The likely ground damage arising from liquefaction of the soils in the Porirua Basin Study Area is shown on Figure 12, based on the assessment outlined in Section 8. The ground damage potential has been classified into the following zones, as shown on the ground damage map on Figure 12:

- Potential for lateral spreading and large subsidence during both Scenarios 1 and 2.
- Potential for lateral spreading during Scenario 2 only, and subsidence during both Scenarios 1 and 2.
- Potential for subsidence during both Scenarios 1 and 2.
- Potential for subsidence during Scenario 2, and only minor subsidence during Scenario 1.
- Potential for subsidence during both Scenarios 1 and 2, but not widespread.
- Potential for minor subsidence during Scenario 2 only.

10 LIMITATIONS

The liquefaction hazard study has been carried out as a regional hazard assessment based on the available information and within the available time and resources. It should not be considered as a substitute for site specific site investigations and geotechnical engineering assessment for any project.

The following specific limitations apply for the products of this study:

1. While zones of liquefaction potential have been shown on the map, there is no certainty that liquefaction will occur at a particular area due to an earthquake of any size.

2. It is possible that liquefaction could occur in some isolated areas not shown to be susceptible to liquefaction, for example near streams.

3. The classification of liquefaction potential and ground damage is indicative only, and does not imply any level of damage to particular structures or services.

4. The magnitude of ground damage suggested in the report is indicative only.

5. The boundaries of the various liquefaction and ground damage zones are approximate and indicative only, and should be used with caution.

6. There is limited amount of information in areas such as Plimmerton, Mana and Pauatahanui. Therefore, the estimated lateral extent and potential for liquefaction in these areas are indicative only.

7. Site specific assessment should be undertaken where the performance of a particular site is required.

REFERENCES

Ambraseys, N N (1988). Liquefaction-Induced Ground Failures. Journal Earthquake Engineering & Structural Dynamics, Vol 17, No.1, September 1988.

American Society of Civil Engineers (1978). Definition of Terms Related to Liquefaction. Report submitted by the Committee on Soil Dynamics of the Geotechnical Engineering Division of the American Society of Civil Engineers (ASCE). ASCE Journal of the Geotechnical Engineering Division. Vol 104. No GT9.

Berrill, J B and Davis, R O (1985). Energy Dissipation and Seismic Liquefaction of Sands : Revised Model. Soils and Foundations Vol, 25 No 2 106-118, June 1985. Japanese Society of Soil Mechanics and Foundation Engineering.

Centre for Advanced Engineering (1992). Lifelines in Earthquakes, Wellington Case Study. Project Report. University of Canterbury, Christchurch, NZ, August 1991.

Dellow, G D, Read, SAL, Begg, J G, Van Dissen, R J and Perrin, N D (1992). Distribution of Geological Materials in Lower Hutt and Porirua, New Zealand : A Component of a ground shaking hazard assessment. Submitted for publication in the Bulletin of the NZ Nat. Soc. Earthquake Engrg.

Department of Scientific and Industrial Research (1967). NZ Geological Map. 1:250,000. Sheet 12 Wellington.

DSIR (1980). Pauatahanui Inlet - An Environmental Study. DSIR Information Series 141, Co-ordinated by W B Healy of the Soil Bureau, Wellington, New Zealand.

DSIR (1990). Report on Resonant Alluvium Conditions for Part of Porirua Basin. (Part of 1989 Study) By Stephenson, W R, Barker, P R and New, G. Prepared for Wellington Regional Council. Regional Natural Disaster Reduction Plan - Seismic Hazard. Division of Land and Soil Sciences Contract 90/5, March 1990.

Department of Scientific and Industrial Research (1991a). Geological Setting of the Porirua Basin, Including Distribution of Materials and Geotechnical Properties (Part 6 of 1990 Study). Regional Natural Disaster Reduction Plan - Seismic Hazard. Prepared for Wellington Regional Council. Contract Report No .1991/46 By Dellow, G D, Read, SAL, Van Dissen, R J and Perrin, N D, May 1991.

DSIR (1991b). Ground Shaking Hazard Map for The Lower Hutt and Porirua Areas : A Summary Report (Part 8 of 1990 Study). Regional Natural Disaster Reduction Plan - Seismic Hazard. Prepared for the Wellington Regional Council. Contract Report No. 1991/42. By Van Dissen, R J, June 1991.

I R Brown Associates (1991). Seismic Hazard Assessment of Lower Hutt City. Prepared for Lower Hutt City Council. Wellington, June 1991.

Institute of Geological and Nuclear Sciences (1992). Assessment of Liquefaction and Ground Failure Hazards in the Greater Wellington Region, 1992-93, Stage 1. Beetham, R D, and Hancox, G T. IGNS Contract Report No. 1992/84.

Ishihara, K (1985). Stability of Natural Deposits During Earthquakes, Proceedings of the Eleventh International Conference on Soil Mechanics and Foundation Engineering, A A Balkema Publishers, Rotterdam, Netherlands.

National Research Council (1985). Liquefaction of Soils during Earthquakes. Committee on Earthquakes Engineering. Commission on Engineering and Technical Systems. National Academy of Sciences. National Academy Press, Washington DC.

Seed, H B and Idriss, I M (1982). Ground Motions and Soil Liquefaction during Earthquakes. Earthquake Engineering Research Institute, Monograph Series.

Standards Association of New Zealand (1986). Methods of Testing Soils for Civil Engineering Purposes. NZS 4402 : 1986. Wellington.

Standards Association of New Zealand (1988). Methods of Testing Soils for Civil Engineering Purposes. NZS 4402 : 1988. Supplement. Wellington.

Tokimatsu, K and Seed, H B (1987). Evaluation of Settlements in Sands Due to Earthquake Shaking. Journal of Geotechnical Engineering. ASCE. Vol. 113, No.8, pp 861-878.

Tsuchida, H (1971). Estimation of Liquefaction Potential of Sandy Soils. Proc. Third Joint Meeting, US-Japan Panel on Wind and Seismic Effects. UJNR, May 1971.

Works Consultancy Services (1993a). A Review of Historical Records of Liquefaction. Liquefaction Hazard Study, Wellington Region. Prepared for the Wellington Regional Council. McMinn, J A, Brabhaharan, P, and Jennings, D N. May 1993.

Works Consultancy Services (1993b). Liquefaction Hazard Study, Wellington Region. Study Area 1 Wellington City. Prepared for the Wellington Regional Council. Brabhaharan, P, and Jennings, D N. May 1993.

Works Consultancy Services (1993c). Liquefaction Hazard Study, Wellington Region. Study Area 2 Hutt Valley. Prepared for the Wellington Regional Council. Brabhaharan, P, and Jennings, D N. May 1993.

Works Consultancy Services (1993d). Liquefaction Hazard Study, Wellington Region. Study Area 4 Kapiti Coast. Prepared for the Wellington Regional Council. Brabhaharan, P, and Jennings, D N. May 1993.

Works Consultancy Services (1993e). Liquefaction Hazard Study, Wellington Region. Study Area 5 Wairarapa. Prepared for the Wellington Regional Council. Brabhaharan, P, and Jennings, D N. May 1993.

Tables

Zones	Scenario 1		Scenario 2	
	MM Intensity	Peak Ground Acceleration (g)	MM Intensity	Peak Ground Acceleration (g)
1	V-VI	0.02-0.06	VIII	0.3-0.6
2	VI	0.02-0.1	VIII-IX	0.3-0.6
5	VIII-IX	<0.3 generally between 0.1-0.2	X-XI	0.5-0.8

Title
GROUND SHAKING PARAMETERS

WORKS Consultancy Services	Location LIQUEFACTION HAZARD STUDY PORIRUA BASIN	Job No. C2375.00
	Client WELLINGTON REGIONAL COUNCIL	Table 1

Key Borehole	Sub-Area	Liquefacton [Yes = Y, No = N]	
		Scenario 1	Scenario 2
PL1	Plimmerton	Y	Y
MA1	Mana	Y	Y
PAR	Paremata	Y	Y
PAU	Pauatahanui	Y	Y
TI1	Titahi Bay	N	Y
PO1	Porirua Harbour and City	Y	Y
PO2	Porirua Harbour and City	Y	Y
PO3	Porirua Harbour and City	Y	Y
PO4	Porirua Harbour and City	Y	Y
PO5	Porirua Harbour and City	Y	Y
PO6	Porirua Harbour and City	Y/N?	Y

Notes
1. For assessment of liquefaction potential, see Figures 8 and 9
2. For location of key boreholes, see Figure 4.
3. For summary logs of key boreholes, see Figure 5.

Title

LIQUEFACTION ASSESSMENT

WORKS Consultancy Services

Location: LIQUEFACTION HAZARD STUDY PORIRUA BASIN

Job No. C2375.00

Client: WELLINGTON REGIONAL COUNCIL

Table 2

Key Borehole	Scenario 1		Scenario 2	
	Estimated Thickness of Liquefiable Layer(s) (m)	Estimated Order of Subsidence (mm)	Estimated Thickness of Liquefiable Layer(s) (m)	Estimated Order of Subsidence (mm)
PL1	6.8	300	6.8	300
PA	11.7	300	16.8	400
PAU	0.8	25	1.5	25
TI1	-	-	1.4	50
PO1	1.7	50	1.7	50
PO2	7.3	100	12.1	200
PO3	4.9	150	5.9	200
PO4	5.0	200	5.0	200
PO5	0.6	25	2.8	100
PO6	-	-	1.5	25

Title

APPROXIMATE LIQUEFACTION INDUCED SUBSIDENCE

WORKS Consultancy Services

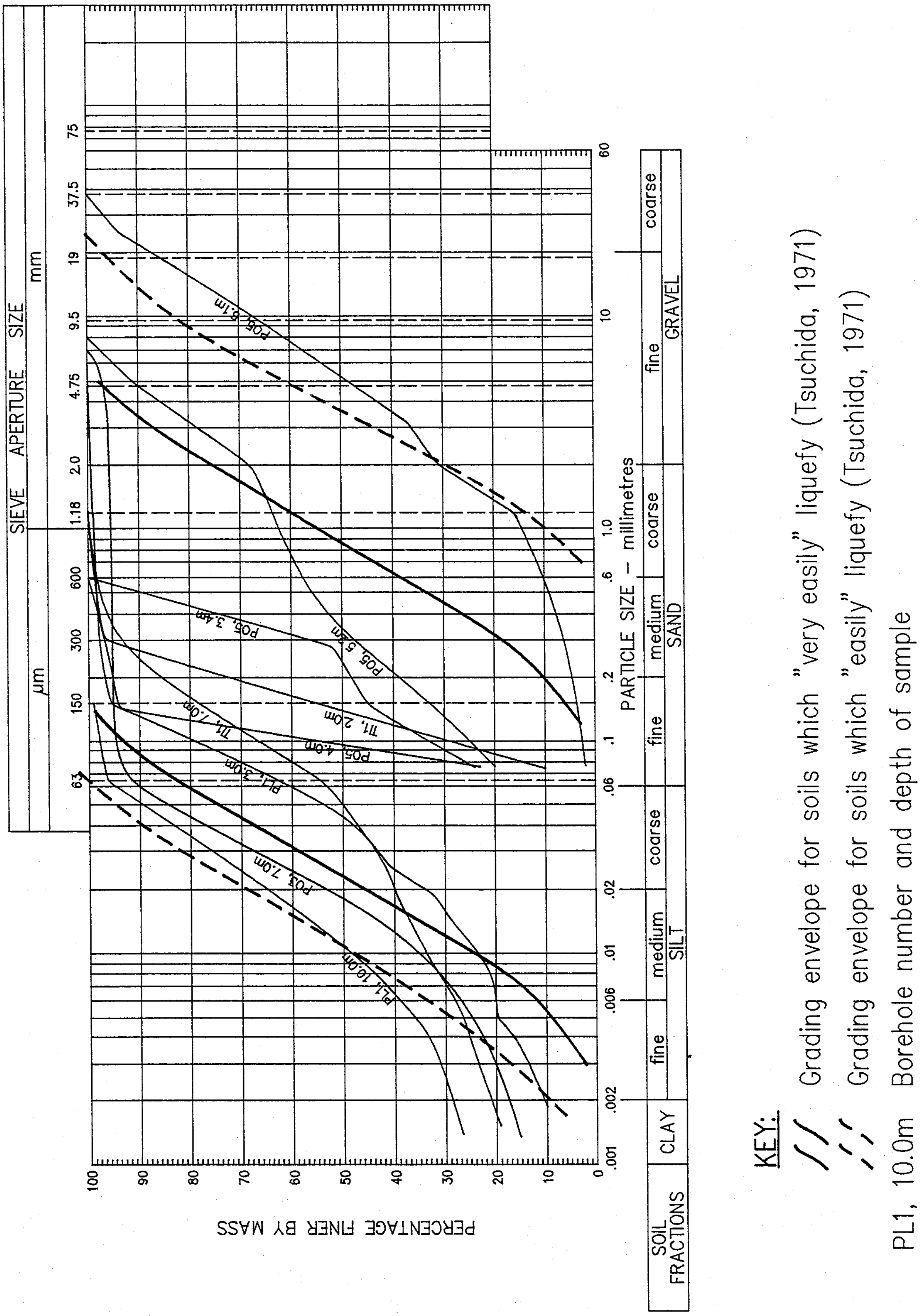
Location: LIQUEFACTION HAZARD STUDY PORIRUA BASIN

Job No. C2375.00

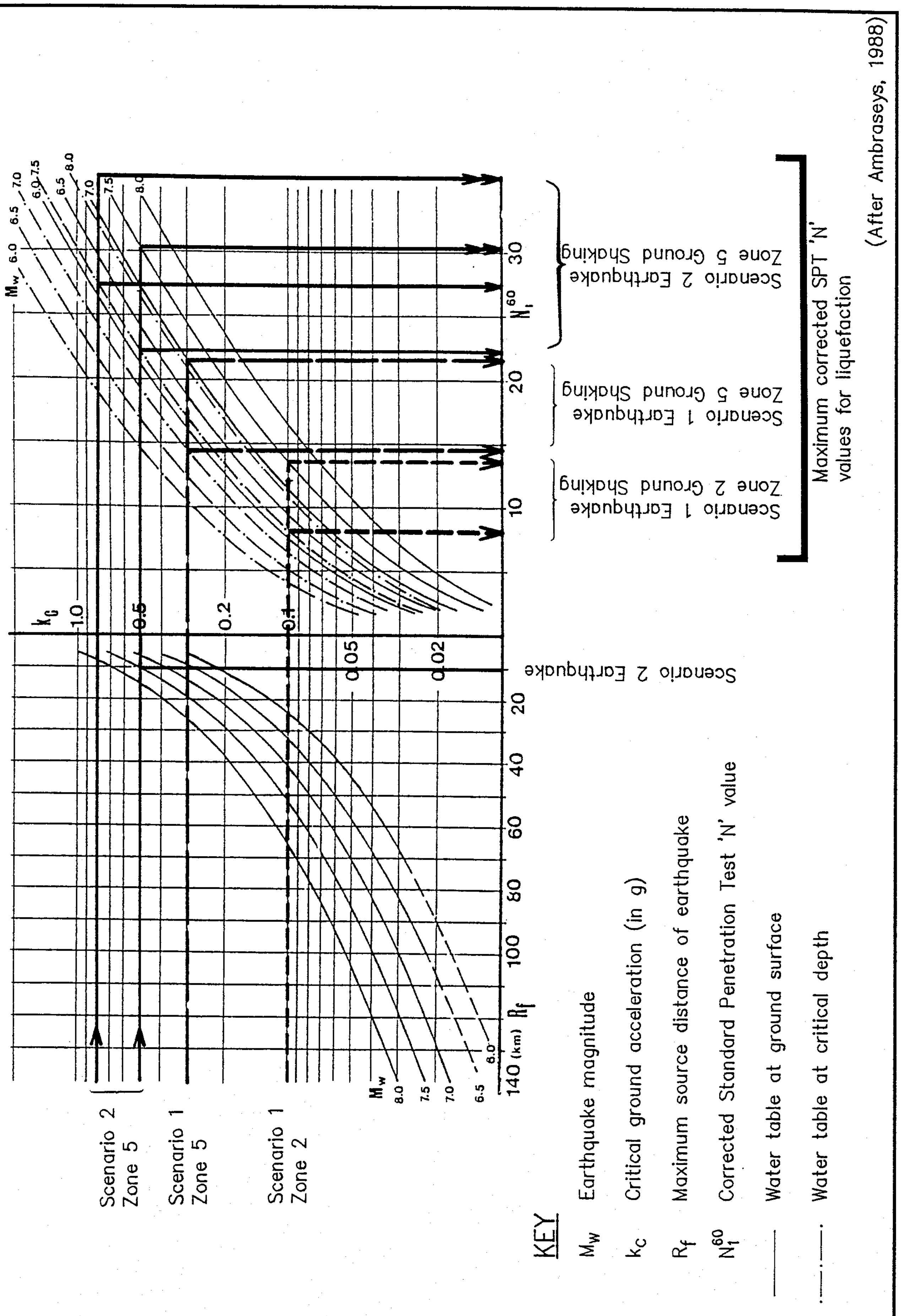
Client: WELLINGTON REGIONAL COUNCIL

Table 3

Figures



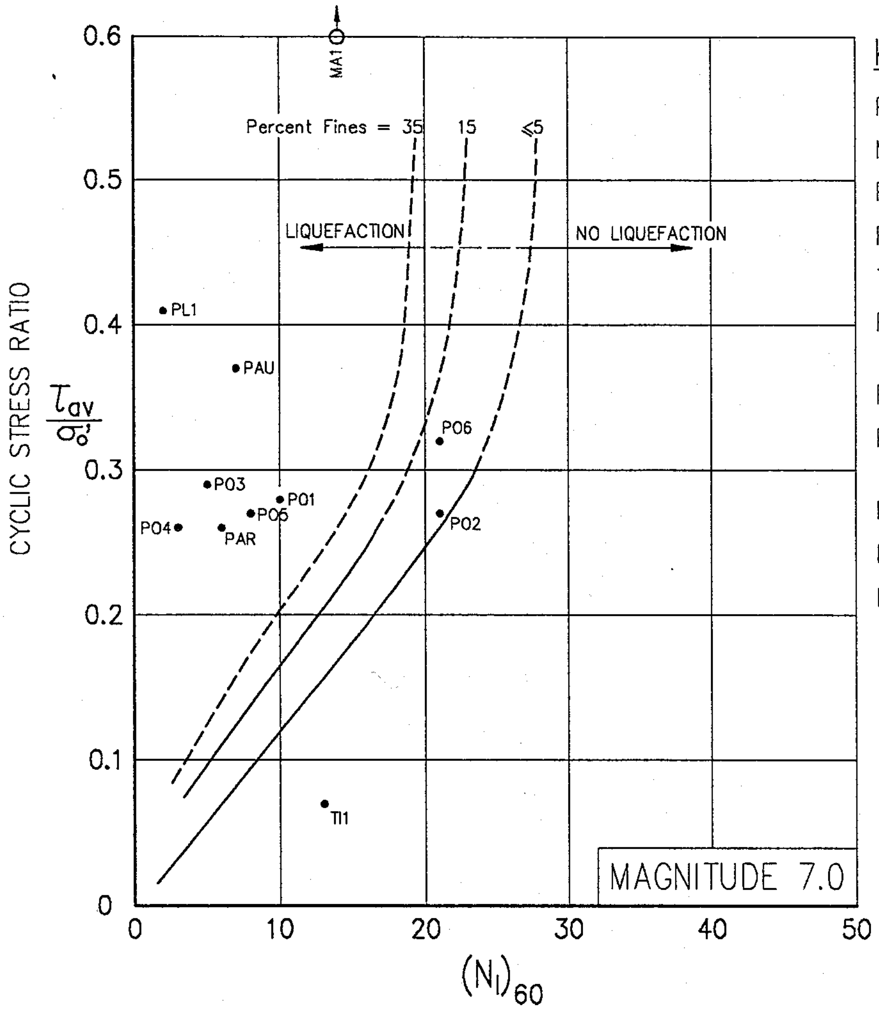
Title		
PARTICLE SIZE DISTRIBUTION AND LIQUEFACTION SUSCEPTIBILITY		
WORKS Consultancy Services	Location: LIQUEFACTION HAZARD STUDY PORIRUA BASIN	Job No. C2375.00
	Client: WELLINGTON REGIONAL COUNCIL	Figure 6



Title

LIQUEFACTION SUSCEPTIBILITY - BASED ON AMBRASEYS' METHOD

WORKS Consultancy Services	Location: LIQUEFACTION HAZARD STUDY PORIRUA BASIN	Job No.: C2375.00
	Client: WELLINGTON REGIONAL COUNCIL	Figure: 7



CORRECTED STANDARD PENETRATION TEST VALUES

KEY TO BOREHOLES:

PL1	PLIMMERTON DOMAIN
MA1	MANA MARINA
PAR	PAREMATA BRIDGE
PAU	PAUATAHANUI BRIDGE
TI1	TITAHI BAY–KURA PARK
PO1	PORIRUA TECHNICAL INSTITUTE, ELSDON
PO2	WAREHOUSE, ELSDON
PO3	PORIRUA RAMP BRIDGE REPLACEMENT
PO4	PORIRUA TOWN CENTRE
PO5	PORIRUA TOWN CENTRE
PO6	MUNGAVIN INTERCHANGE

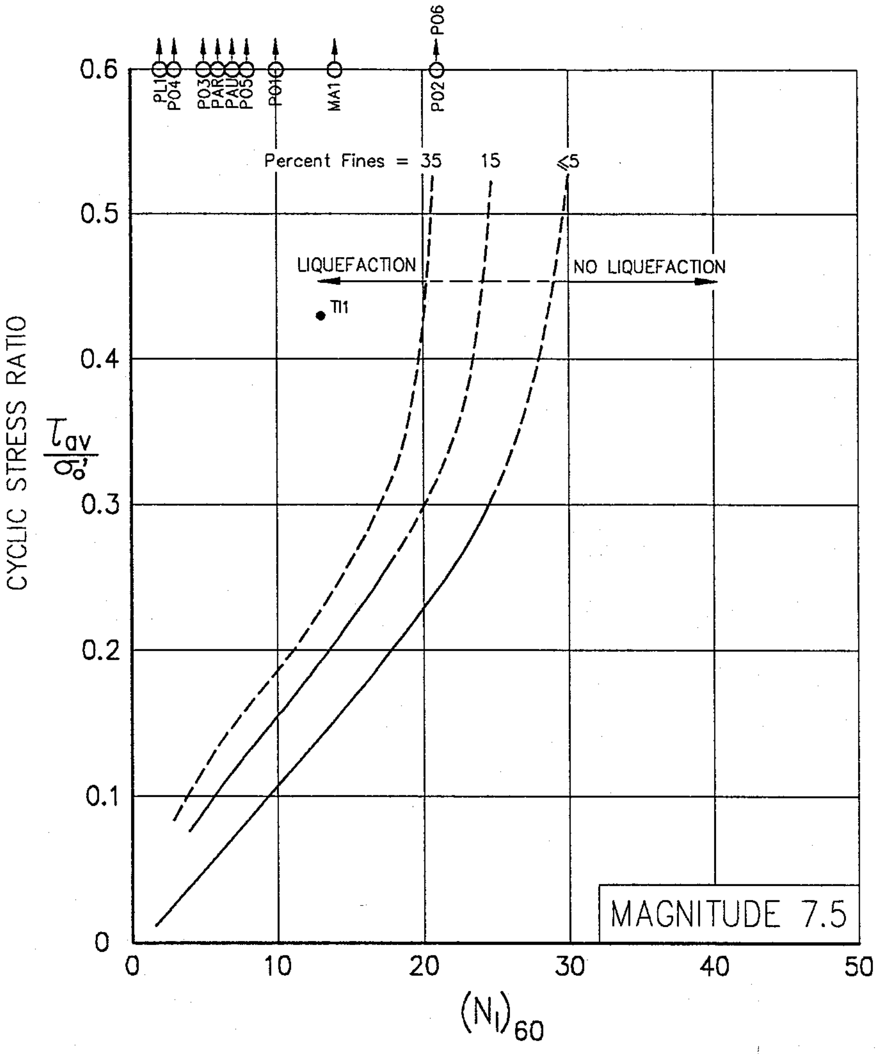
NOTE:

1. THE EMPIRICAL CURVES SHOW SEPARATE REGIONS OF THE PLOT OF 'LIQUEFACTION' AND 'NO LIQUEFACTION'.

2. THE FAMILY OF CURVES ARE FOR SANDS WITH DIFFERENT MAXIMUM PERCENTAGES OF FINES, SILT AND CLAY PASSING 63μm SIEVE.

AFTER SEED AND IDRISS (1982) AND SEED ET AL (1984)

Title	ASSESSMENT OF LIQUEFACTION POTENTIAL – SCENARIO 1 EARTHQUAKE	
WORKS Consultancy Services	Location: LIQUEFACTION HAZARD STUDY PORIRUA BASIN	Job No. C2375.00
	Client: WELLINGTON REGIONAL COUNCIL	Figure 8



KEY TO BOREHOLES:

PL1	PLIMMERTON DOMAIN
MA1	MANA MARINA
PAR	PAREMATA BRIDGE
PAU	PAUATAHANUI BRIDGE
TI1	TITAHI BAY–KURA PARK
PO1	PORIRUA TECHNICAL INSTITUTE, ELSDON
PO2	WAREHOUSE, ELSDON
PO3	PORIRUA RAMP BRIDGE REPLACEMENT
PO4	PORIRUA TOWN CENTRE
PO5	PORIRUA TOWN CENTRE
PO6	MUNGAVIN INTERCHANGE

NOTE:

1. THE EMPIRICAL CURVES SHOW SEPARATE REGIONS OF THE PLOT OF 'LIQUEFACTION' AND 'NO LIQUEFACTION'.

2. THE FAMILY OF CURVES ARE FOR SANDS WITH DIFFERENT MAXIMUM PERCENTAGES OF FINES, SILT AND CLAY PASSING 63μm SIEVE.

AFTER SEED AND IDRISS (1982) AND SEED ET AL (1984)

Title: ASSESSMENT OF LIQUEFACTION POTENTIAL – SCENARIO 2 EARTHQUAKE		
WORKS Consultancy Services	Location: LIQUEFACTION HAZARD STUDY PORIRUA BASIN	Job No. C2375.00
	Client: WELLINGTON REGIONAL COUNCIL	Figure 9

Appendix A

SITE INVESTIGATION RESULTS

Borehole Logs

ENGINEERING GEOLOGY SECTION

LOG OF DRILL HOLE

HOLE NO. BH 1

PROJECT Liquefaction Study FEATURE .... LOCATION Titahi Bay - Kura Park

GRID REF. .... M.W.D. CO-ORD. .... DATUM MSL

ANGLE FROM HORIZONTAL 90° DIRECTION .... H.A.D. GROUND .... H.A.D. COLLAR ....

DESCRIPTION OF CORE (weathering, hardness, strength, colour, rock or soil type, defect spacing, lithological features (bedding, foliation, mineralogy, texture, cement, etc), stratigraphic name)	SAMPLE TYPE	DEPTH H.A.D.	ROCK DEFECTS (OR SOIL DESCRIPTION)	WATER LEVEL	STANDARD PENETRATION TEST (SPT)
FILL: Brown (orange yellow mottles) silty SAND.	WB		Borehole casing from 0.0 to 3.0m. Very loose; moist fine to medium sand; silt. Water level 0.85m : 7/1/93	∇ (0.85m)	
FILL: Soft-firm, moderately plastic orange/yellow mottled brown clayey SILT, damp		0.9 – 1.1	SPT at 1.0m-1.45m		
	SPT	1.0 – 1.1			1 1 2 2 2 2, N = 8
Brown (with orange and yellow mottles) silty SAND	WB		tightly packed, moist fine to medium sand; silt. 2.0m DS: A and B		
	SPT, SS	2.0	SPT at 2.0m-2.45m		1.5 2 2 4 5 7, N = 18
	WB				
	SPT	3.0	SPT at 3.0m-3.45m		4 3 4 2 5 5, N = 16
colour change	WB		DS: 4.0m		
Same material as above colour change to light brown grey with orange mottles.	SPT, SS	4.0	SPT at 4.0m-4.45m		3 3 4 5 6 6, N = 21
	WB				
	SPT	5.0	SPT at 5.0-5.45m		2 5 5 5 8 8, N = 26
			SPT at 6.0m-6.45 N=1.5		
Brown sandy SILT with (some or rare?) clay.	UB	5.8 – 6.2	Soft, moderately plastic; silt sand-fine; and some clay. Contains some root fragments. DS: 6.0m		
	SPT, SS	6.0			0 0 0 0 0 1.5, N = 1.5
Green grey, sandy SILT with some clay interbedded with grey sandy SILT.	WB	6.2	Soft; moderately plastic; moist silt; sand; clay. Contains root fragments		
		7.0	DS: 7.05-7.15m; DS: 7.15-7.30		
	SR	7.5	tightly packed moist; silt; sand.		

DRILLER:	ROCK WEATHERING	ROCK HARDNESS	FRACTURE LOG		
Pendelton	UW - Unweathered	VH - Very hard	(cms) Spacing of natural fractures	LOGGED: MJF	PROJECT Liquefaction
STARTED: 6/1/93	SW - Slightly weathered	H - Hard	Fractures/m of core	DATE: 6/1/93	HOLE NO BH 1
FINISHED: 7/1/93	MW - Moderately weathered	MH - Moderately hard		TRACED:	LENGTH 9.7m
DRILL:	HW - Highly weathered	MS - Moderately soft		CHECKED:	
	CW - Completely weathered	S - Soft		ORIGINAL VERTICAL:	CORE BOXES
		VS - Very soft		SCALE:	
				SHEET 1 OF 2	DRG NO

EXPLANATION

SPT : Standard Penetration Test.
DS : Disturbed Soil Sample.
SR : Split Ring Sampler.
SS : Split spoon Sampler. (SPT)
WB : Wash boring

ENGINEERING GEOLOGY SECTION

LOG OF DRILL HOLE

HOLE NO. BH. 1.

PROJECT Liquefaction Study FEATURE .... LOCATION Titahi Bay - Kura Park

GRID REF. .... M.W.D. CO-ORD. .... DATUM ....

ANGLE FROM HORIZONTAL 90° DIRECTION .... H.A.D. GROUND .... H.A.D. COLLAR ....

DESCRIPTION OF CORE (Weathering, hardness, strength, colour, rock or soil type, defect spacing, lithological features (bedding, foliation, mineralogy, texture, cement, etc), stratigraphic name)	Sample type	Depth H.A.D.	Rock defects (or soil description) (consistency, compactness, water content, group symbol etc)	Standard Penetration Test (SPT)
Green grey; sandy SILT with some Clay, interbedded with Grey sandy SILT (or silty SAND)	WB		Soft; moderately plastic; moist silt; sand. Contains root fragments	
		8.0	DS: 8.0m - 8.45m SPT at 8.0m - 8.45m	1 1 3 6 7 6
	SPT			N = 22
	SS		tightly packed; silt; sand fine to coarse.	
	WB			
Grey green silty SAND with some gravel.			DS: 9.0m - 9.45m	6 9 14 27
	SPT	9.0	SPT at 9.0m - 9.30m N = 50+ per 40mm	
	SS		End test - zero penetration per blow.	
	WB		Very dense; sand, silt gravel	
End of Borehole at 9.7m			UW to SW; slightly to moderately cemented, extremely strong SILTSTONE.	
			SPT at 9.7m; N = 46/50mm	
			Standpipe 0.1m to 8.0m depth.	

DRILLER: Pendelton

STARTED: 6/1/93

FINISHED: 7/1/93

DRILL: ....

ROCK WEATHERING
- UW - Unweathered
- SW - Slightly weathered
- MW - Moderately weathered
- HW - Highly weathered
- CW - Completely weathered

ROCK HARDNESS
- VH - Very hard
- H - Hard
- MH - Moderately hard
- MS - Moderately soft
- S - Soft
- VS - Very soft

FRACTURE LOG (cms): Spacing of natural fractures / Fractures/m of core

EXPLANATION
- WB Wash boring
- SPT Standard Penetration Test
- SS Split spoon Sampler (SPT)

LOGGED: M.J.F.
DATE: 6/1/93
TRACED: ....
CHECKED: ....
ORIGINAL VERTICAL: ....
SCALE: ....
SHEET 2 OF 2

PROJECT Liquefaction
HOLE NO. BH 1
LENGTH 9.7m
CORE BOXES ....
DRG NO ....

ENGINEERING GEOLOGY SECTION

LOG OF DRILL HOLE

HOLE NO. BH2

PROJECT: Liquefaction Study FEATURE: .... LOCATION: Plimmerton Domain, Porirua

GRID REF: .... M.W.D. CO-ORD: .... DATUM: ....

ANGLE FROM HORIZONTAL: 90° DIRECTION: .... H.A.D. GROUND: .... H.A.D. COLLAR: ....

DESCRIPTION OF CORE (Weathering, hardness, strength, colour, rock or soil type, defect spacing, lithological features (bedding, foliation, mineralogy, texture, cement, etc), stratigraphic name)	Depth H.A.D. (m)	Sample type	ROCK DEFECTS (OR SOIL DESCRIPTION) (consistency, compactness, water content, group symbol etc)	Water level	Standard Penetration Test (SPT)
TOPSOIL			Ground Water Level 0·3m 8/1/93	▽	
Grey (orange and brown mottles) silty SAND. Interbedded. Brown sandy clay SILT	1·0	WB, SPT, SS	DS: 1·0m – 1·45m SPT at 1·0m – 1·45m N = 4 Very loose; poorly graded; sand–fine to medium; silt. Contains specks of mica, with some shell fragments.		½ ½ ½ ½ 1 2 N = 4
	2·0	WB, SPT, SS	DS: 2·0m – 2·45m SPT at 2·0m – 2·45m Very soft; moderately plastic silt; sand; clay		½ ½ 1 1 1 1 N = 4
Grey silty SAND	2·6 – 3·0	WB, SPT, SS	Very loose; moist sand-fine to medium; SILT; contains shell fragments with specks of mica DS: 3·0m – 3·45m SPT at 3·0m – 3·45m N = 1⅓		⅓ ⅓ ⅓ ⅓ ⅓ ⅓ N = 1⅓
	4·0	WB, SPT, SS	DS: 4·0m – 4·45m SPT at 4·0m – 4·45m N = 1		¼ ¼ ¼ ¼ ¼ ¼ N = 1
Brown, sandy SILT with rare clay.	4·4 – 5·0	OB	Very soft; moist; moderately plastic SILT; sand; clay. Contains minor root fragments. DS: 4·5 to 4·6m DS: 5·0m – 5·45m SPT: 5·0m – 5·45 N = 6		½ ½ 1 2 1 2 N = 6
Grey silty SAND	5·1	SPT, SS, WB	Very loose; moist; sand-fine; silt. Contains shell fragments with specks of mica DS: 6·0m – 6·45m SPT: 6·0m – 6·45m N = 1 blow per 450mm		⅙ ⅙ ⅙ ⅙ ⅙ ⅙
Brown grey sandy SILT with rare clay	6·0 – 7·0	SPT, SS, WB, SPT, SS	Very soft; moderately plastic moist; silt, sand-fine; clay contains minor root fragments with wood and shell fragments DS: 7·0m – 7·45 SPT: 7·0m – 7·45 N = 1 blow per 450mm		⅙ ⅙ ⅙ ⅙ ⅙ ⅙

DRILLER: Pendelton

STARTED: 7/1/93

FINISHED: 8/1/93

DRILL: ....

ROCK WEATHERING: UW – Unweathered; SW – Slightly weathered; MW – Moderately weathered; HW – Highly weathered; CW – Completely weathered

ROCK HARDNESS: VH – Very hard; H – Hard; MH – Moderately hard; MS – Moderately soft; S – Soft; VS – Very soft

FRACTURE LOG (cms): 100 50 10 5 1 0·1 — Spacing of natural fractures; 1 2 10 20 100 1000 — Fractures/m of core

EXPLANATION
- SS : Split Spoon (SPT)
- DS : Disturbed Soil Sample
- SR : Split Ring Sample
- SPT Standard Penetration Test
- OB open barrel sampler

LOGGED: MJF

DATE: 7/1/93

TRACED: ....

CHECKED: ....

ORIGINAL VERTICAL: ....

SCALE: ....

PROJECT: Liquefaction

HOLE NO: 2

LENGTH: 15·0m

CORE BOXES: ....

SHEET 1 OF 2

DRG NO: ....

ENGINEERING GEOLOGY SECTION

LOG OF DRILL HOLE

HOLE NO. BH2

PROJECT Liquefaction Study FEATURE .... LOCATION Plimmerton Domain Porirua

GRID REF. .... M.W.D. CO-ORD. .... DATUM ....

ANGLE FROM HORIZONTAL 90° DIRECTION .... H.A.D. GROUND .... H.A.D. COLLAR ....

DESCRIPTION OF CORE (WEATHERING, HARDNESS, STRENGTH, COLOUR, ROCK OR SOIL TYPE, DEFECT SPACING, LITHOLOGICAL FEATURES (bedding, foliation, mineralogy texture, cement, etc), STRATIGRAPHIC NAME)	ROCK WEATHERING (SW MW HW)	ROCK HARDNESS (H MH MS S)	SAMPLE TYPE	CORE LOSS/LIFT %	DEPTH H.A.D. (Core size, casing)	GRAPHIC LOG	FRACTURE LOG (Spacing of natural fractures)	ROCK DEFECTS (PROMINENT JOINTS, BEDDING, SEAMS, VEINS, SHATTER, SHEAR, AND CRUSH ZONES, FOLIATION SCHISTOSITY (attitude, width, spacing, smoothness)) (OR SOIL DESCRIPTION) (consistency, compactness, water content, group symbol etc)	DATE/DEPTH	R.Q.D. %	WATER LEVEL	DRILL WATER LOSS %	STANDARD PENETRATION TEST (SPT)
Brown grey SILT with some sand and clay			WB		8.0			Very soft; plastic: moist silt; sand fine; clay. Minor root wood and shell fragments present. DS: 8.0m-8.45m SPT: 8.0m-8.45m					0 0 0 ½ 1½ 1½ N = 3.5
Brown grey silty SAND			SPT SS / WB / SPT SS / WB		9.0			Very loose; moist; sand; silt. Contains mica speckles and shell fragments. DS: 9.0m-9.45m SPT: 9.0m-9.45					½ ½ 1 1 1 2 N = 5
Green grey SILT with some sand and clay			SPT SS / WB / SPT SS		10.0, 11.0			DS: 10.0m-10.45m SPT: 10.0m-10.45m. Soft; moderately plastic; silt sand-fine; clay. Contains some root and shell fragments. DS: 11.0m-11.45m SPT: 11.0m-11.45m					½ ½ 1 1 1 2 N = 5; 1 1 3 2 1 2 N = 8
Green grey clayey SILT					12.0, 13.0, 14.0, 15.0			Soft; moderately plastic; moist silt; clay. Contains some root fragments. DS: 12.0m-12.45m SPT: 12.0m-12.45m. DS: 13.0m-13.45m SPT: 13.0m-13.45m. DS: 14.0m-14.45m SPT: 14.0m-14.45m. DS: 15.0m-15.45m SPT: 15.0m-15.45m N = 4.5					1 1 1½ 1 2 3 N = 7.5; ⅓ ⅓ ⅓ ½ 1 1 N = 2.75; ¼ ¼ ¼ ¼ ½ 1 N = 2; ½ ½ 1 1 1½ 2

DRILLER: ....

STARTED: ....

FINISHED: ....

DRILL: ....

ROCK WEATHERING
UW - Unweathered
SW - Slightly weathered
MW - Moderately weathered
HW - Highly weathered
CW - Completely weathered

ROCK HARDNESS
VH - Very hard
H - Hard
MH - Moderately hard
MS - Moderately soft
S - Soft
VS - Very soft

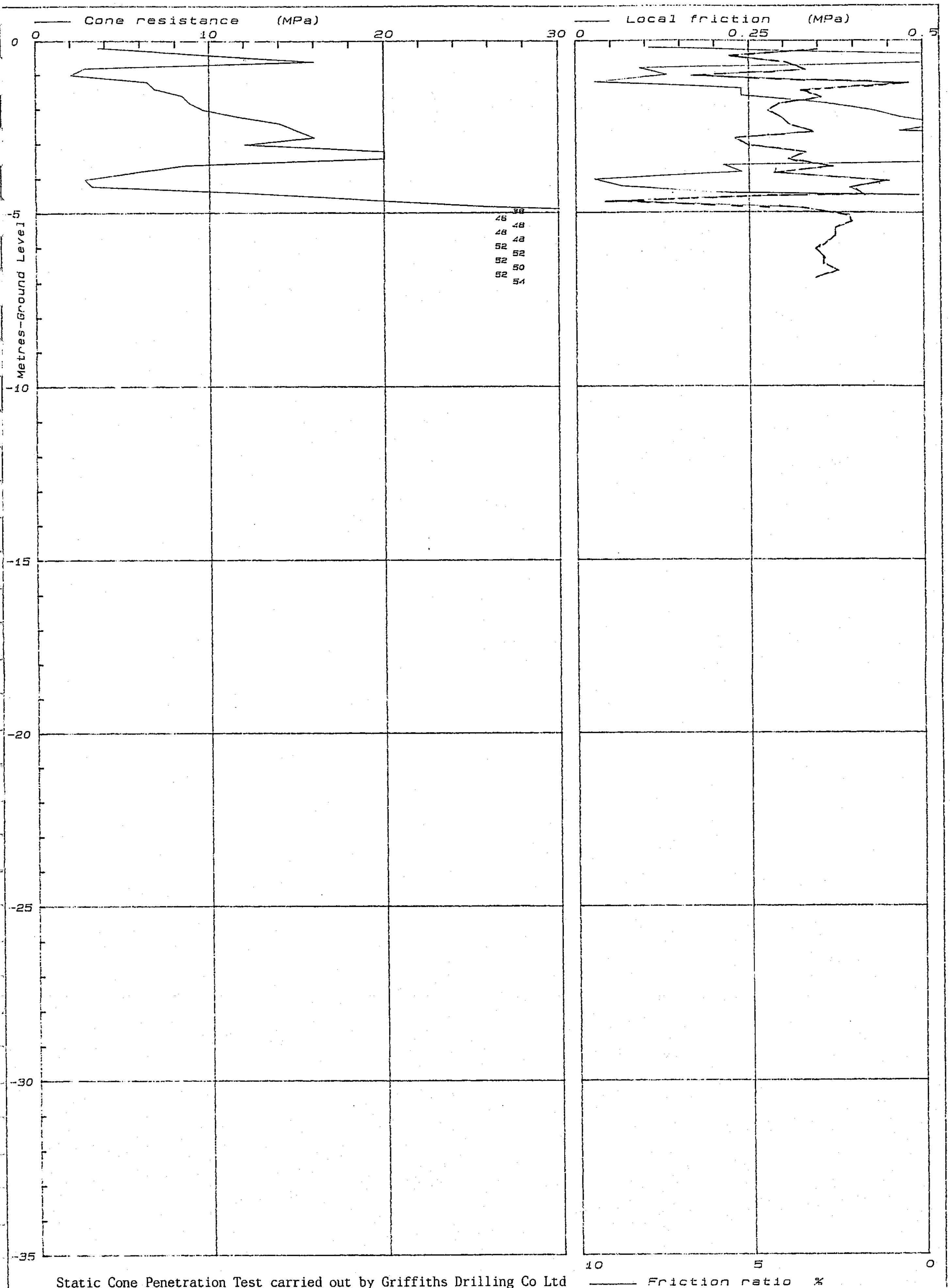
FRACTURE LOG (cms) Spacing of natural fractures; Fractures/m of core

EXPLANATION
SS: Split Spoon (SPT)
DS: Disturbed soil sample.
SR: Split Ring Sampler.
SPT: Standard Penetration Test.
OB: Open barrel Sampler.

LOGGED: M.J.F. DATE: 8/1/93 TRACED: .... CHECKED: .... ORIGINAL VERTICAL: .... SCALE: .... SHEET 3 OF 3

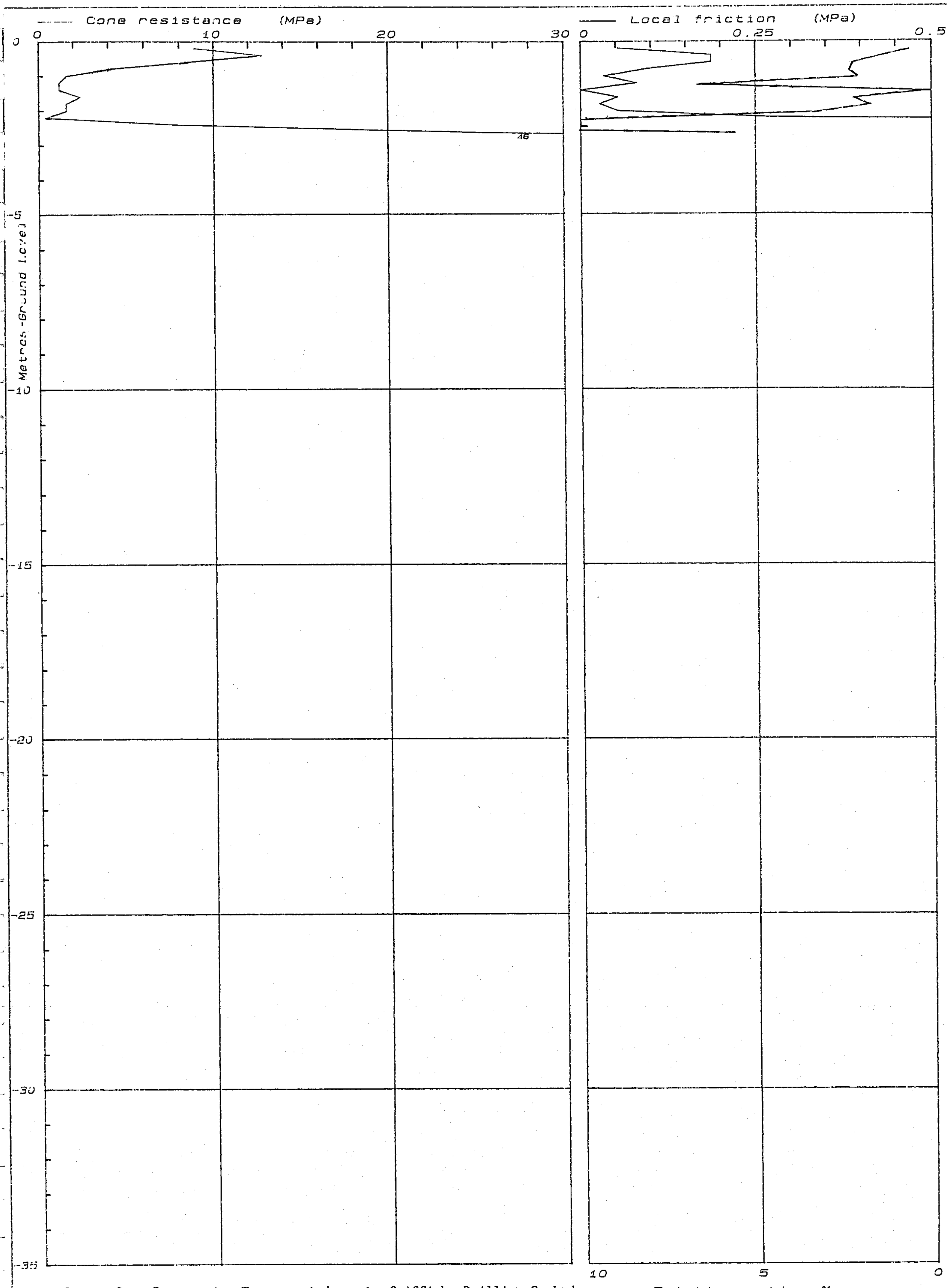
PROJECT Liquefaction HOLE NO BH2 LENGTH 15.45 CORE BOXES .... DRG NO ....

Static Cone Penetration Test Results



Static Cone Penetration Test carried out by Griffiths Drilling Co Ltd

WORKS Consultancy Services	Titahi Bay	Date: 08-01-93	Job No
		C Reeve	CPT 2
	Wellington	Sheet 1 of 1	



Static Cone Penetration Test carried out by Griffiths Drilling Co Ltd ——— Friction ratio %

WORKS Consultancy Services	Mana Ngatitoa Domain Wellington	Date: 08-01-93	Job No
		C Reece	CPT 1
		Sheet 1 of 1	

Laboratory Test Results

WORKS Consultancy Services

CENTRAL LABORATORIES
Hutt Park Road, PO Box 30-845, Lower Hutt, New Zealand
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Report No GE093/350

CLASSIFICATION TEST RESULTS

NZS 4402: 1986 tests 2.2.1, 2.3.1, 2.5, 2.4.1   NZS 4407: 1991 tests 3.3, 3.2, 3.4

CLIENT ... WORKS WELLINGTON CONSULTANCY   SAMPLE NO. 2-93/1,2,3,4
PROJECT ... LIQUEFACTION STUDY   TESTED BY ... MJM
SOURCE ... KURA PARK ...... PLIMERTON DOMAIN   DATE ... 11. 1. 93
DESCRIPTION ... ———   CHECKED BY ... SW

C.L. SAMPLE NO.	CLIENT I.D.	AS RECEIVED w (%)	SAMPLE PREP. WHOLE / -425µm / OTHER	SAMPLE PREP. NATURAL / AIR DRIED / OVEN DRIED / OTHER / UNKNOWN	ATTERBERGS LL	ATTERBERGS PL	ATTERBERGS PI	C.P.L.	L.S.	PARTICLE DENSITY ρ_s (t/m³)	REMARKS / VISUAL DESCRIPTION
2-93/1	BH1 2.0m KURA PARK	22.5	-	-	-	-	-	-	-	-	SAND: fine grain y-b-grey, some silt
2-93/2	BH1 7.0-7.15m KURA PARK	-	-	-	-	-	-	-	-	-	SILT-SAND: f-m grain, light grey some clay.
2-93/3	BH2 3.0-3.45m PLIMERTON DOMAIN	-	-	-	-	-	-	-	-	-	SILT-SAND: fine grain, brown-grey, some silt and shell frag. trace organics
2-93/4	BH2 10.0-10.45m PLIMERTON DOMAIN	-	WHOLE	NATURAL	47	19	28	-	-	-	Silty CLAY: Med. PI blue grey, trace fine sand.

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APPROVED SIGNATORY: ......
DESIGNATION: TECHNICAL OFFICER
DATE: 14. 1. 93

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WORKS Consultancy Services

Report No ~~GE093~~/350

PARTICLE SIZE DISTRIBUTION

NZS 4402:1986 tests 2.8.1, 2.8.2, 2.8.4 NZS 4407:1991 tests 3.8.1, 3.8.2

CLIENT: WORKS WELLINGTON CONSULTANCY — SAMPLE NO. 2-93/4
PROJECT: LIQUEFACTION STUDY — TESTED BY MJM
SOURCE: BH2 10.0 - 10.45 PLIMERTON DOMAIN — DATE 11.1.93
DESCRIPTION: Silty CLAY: Med PI, blue grey, trace f. sand — CHECKED BY SW
TEST DETAILS (Delete non-applicable) — DATE 14.1.93

TEST METHOD: WET SIEVE (test 2.8.1), ~~DRY SIEVE (test 2.8.2)~~, HYDROMETER (test 2.8.4)
OTHER N.Z.S. 4402:1980 test (9A)/(9B)
HISTORY: NATURAL / ~~AIR DRIED / OVEN DRIED / UNKNOWN~~
DISPERSANT USED SODIUM HEXAMETAPHOSPHATE. PH OF SUSPENSION 9.5

PARTICLE SIZE ANALYSIS				
ALT. SIEVE SIZE	STD. SIEVE SIZE	% FINER	HYDROM. EQV. PART. DIAM.	% FINER
	75 mm		0.0594	89
	63		0.0429	84
	53		0.0311	77
	37.5		0.0227	68
	26.5		0.0165	59
	19.0		0.0123	52
	13.2		0.0083	45
	9.5		0.0064	40
	6.7		0.0047	36
	4.75		0.0037	32
2.36 mm	~~2.0~~	100	0.0015	27
	1.18	100		
	600 µm	100		
	~~425~~			
	300	100		
	150	99		
	63	96		

~~% LOSS = ...~~
% Passing finest sieve by difference

GRAPHICAL PRESENTATION ON PAGE 2. YES / ~~NO~~

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APPROVED SIGNATORY: [signature]
DESIGNATION: TECHNICAL OFFICER
DATE: 14.1.93

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Report No GE093/350

PARTICLE SIZE DISTRIBUTION

NZS 4402:1986 tests 2.8.1, 2.8.2, 2.8.4 NZS 4407:1991 tests 3.8.1, 3.8.2

CLIENT: WORKS WELLINGTON CONSULTANCY — SAMPLE NO. 2-93/2
PROJECT: LIQUEFACTION STUDY — TESTED BY: MJM
SOURCE: BH1 7.0-7.15m KURA PARK — DATE: 11.1.93
DESCRIPTION: SILT-SAND: f-m grain, light grey, some clay. — CHECKED BY: SW
TEST DETAILS (Delete non-applicable) — DATE: 14.1.93

TEST METHOD: WET SIEVE (test 2.8.1), ~~DRY SIEVE (test 2.8.2)~~, HYDROMETER (test 2.8.4)
OTHER N.Z.S. 4402:1980 test (9A)/(9B)
HISTORY: NATURAL / ~~AIR DRIED / OVEN DRIED / UNKNOWN~~
DISPERSANT USED SODIUM HEXAMETAPHOSPHATE .. PH OF SUSPENSION 9.0

PARTICLE SIZE ANALYSIS				
ALT. SIEVE SIZE	STD. SIEVE SIZE	% FINER	HYDROM. EQV. PART. DIAM.	% FINER
	75mm		0.0638	51
	63		0.0461	46
	53		0.0327	46
	37.5		0.0235	42
	26.5		0.0168	39
	19.0		0.0124	37
	13.2		0.0089	33
	9.5		0.0064	29
	6.7		0.0046	26
	4.75		0.0036	25
2.36mm	~~2.0~~	100	0.0015	19
	1.18	100		
	600µm	99		
	~~425~~			
	300	96		
	150	80		
	63	53		

~~% LOSS = ...~~
% Passing finest sieve by difference

GRAPHICAL PRESENTATION ON PAGE 2. YES/~~NO~~

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APPROVED SIGNATORY:
DESIGNATION: TECHNICAL OFFICER
DATE: 14. 1. 93

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Report No GE93/350

PARTICLE SIZE DISTRIBUTION

NZS 4402:1986 tests 2.8.1, 2.8.2, 2.8.4 NZS 4407:1991 tests 3.8.1, 3.8.2

CLIENT WORKS WELLINGTON CONSULTANCY SAMPLE NO. 2-93/3
PROJECT LIQUEFACTION STUDY TESTED BY MJM
SOURCE BH2 3.0-3.45m PLIMERTON DOMAIN DATE 11.1.93
DESCRIPTION SILT-SAND: finegr, b-grey, some silt and shell frag, trace organics. CHECKED BY SW
TEST DETAILS (Delete non-applicable) DATE 14.1.93

TEST METHOD: WET SIEVE (test 2.8.1), ~~DRY SIEVE (test 2.8.2)~~, HYDROMETER (test 2.8.4)
~~OTHER N.Z.S. 4402-1980 test (9A)/(9B)~~

HISTORY: NATURAL / ~~AIR DRIED / OVEN DRIED / UNKNOWN~~
DISPERSANT USED SODIUM HEXAMETAPHOSPHATE PH OF SUSPENSION 9.5

PARTICLE SIZE ANALYSIS

ALT. SIEVE SIZE	STD. SIEVE SIZE	% FINER	HYDROM. EQV. PART. DIAM.	% FINER
	75mm		0.0690	59
	63		0.0498	52
	53		0.0357	46
	37.5		0.0256	41
	26.5		0.0185	32
	19.0		0.0136	29
	13.2		0.0098	23
	9.5		0.0070	20
	6.7	100	0.0049	20
	4.75	99	0.0034	14
	2.36	99	0.0028	13
	1.18	99	0.0020	10
	600µm	98		
	~~425~~			
	300	98		
	150	95		
75µm	~~63~~	66		

~~% LOSS =~~ ....
% Passing finest sieve by difference

GRAPHICAL PRESENTATION ON PAGE 2. YES ~~NO~~

These test results relate only to the samples as received. Their true representation of source material is neither stated nor implied by Central Laboratories.

APPROVED SIGNATORY: ....
DESIGNATION: TECHNICAL OFFICER
DATE: 14.1.93

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WORKS Consultancy Services

Report No GE093/350

PARTICLE SIZE DISTRIBUTION

NZS 4402:1986 tests 2.8.1, 2.8.2, 2.8.4 NZS 4407:1991 tests 3.8.1, 3.8.2

CLIENT: WORKS WELLINGTON CONSULTANCY — SAMPLE NO. 2-93/1
PROJECT: LIQUEFACTION STUDY — TESTED BY: MJM
SOURCE: BH1 2.0m SAMPLE A KURA PK — DATE: 11.1.93
DESCRIPTION: SAND: fine grain, y-b-grey, some silt — CHECKED BY: SW
TEST DETAILS (Delete non-applicable) — DATE: 13.1.93

TEST METHOD: WET SIEVE (test 2.8.1), ~~DRY SIEVE (test 2.8.2), HYDROMETER (test 2.8.4)~~
~~OTHER N.Z.S. 4402:1980 test (7A)/(9B)~~

HISTORY: NATURAL / ~~AIR DRIED / OVEN DRIED / UNKNOWN~~
DISPERSANT USED: SODIUM HEXAMETA PHOSPHATE — PH OF SUSPENSION: /

PARTICLE SIZE ANALYSIS

ALT. SIEVE SIZE	STD. SIEVE SIZE	% FINER	HYDROM. EQV. PART. DIAM.	% FINER
	75 mm			
	63			
	53			
	37.5			
	26.5			
	19.0			
	13.2			
	9.5			
	6.7			
	4.75			
2.36mm	~~2.0~~			
	1.18	100		
	600 µm	99		
	~~425~~			
	300	97		
	150	56		
75µm	~~63~~	10		

~~% LOSS~~ ....
% Passing finest sieve by difference

GRAPHICAL PRESENTATION ON PAGE 2. ~~YES~~ / NO

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DESIGNATION: TECHNICAL OFFICER
DATE: 13.1.93

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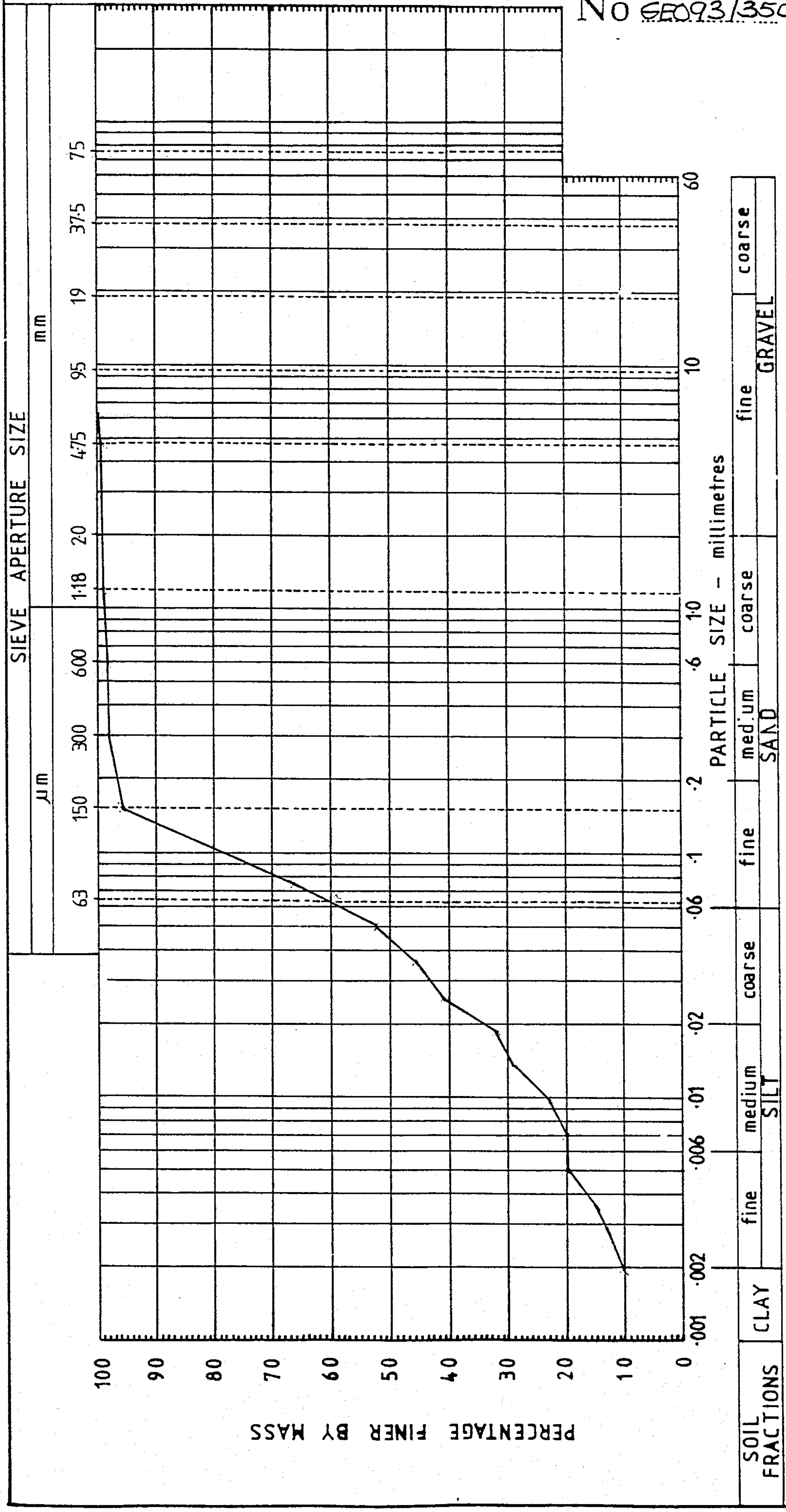
No GE093/350



DRAWING No.

	NAME	DATE
Tested by	MJW	11.1.93
Plotted by	MJW	14.1.93
Checked by	SW	14.1.93

SAMPLE No 2-93/3

DEPTH m. 3.0 – 3.45

WET / ~~DRY~~ SIEVE

PARTICLE SIZE DISTRIBUTION

CLIENT: WORKS WELLINGTON CONSULTANCY

PROJECT: LIQUEFACTION STUDY

SOURCE: BH2 3.0 – 3.45m PLIMERTON DOMAIN

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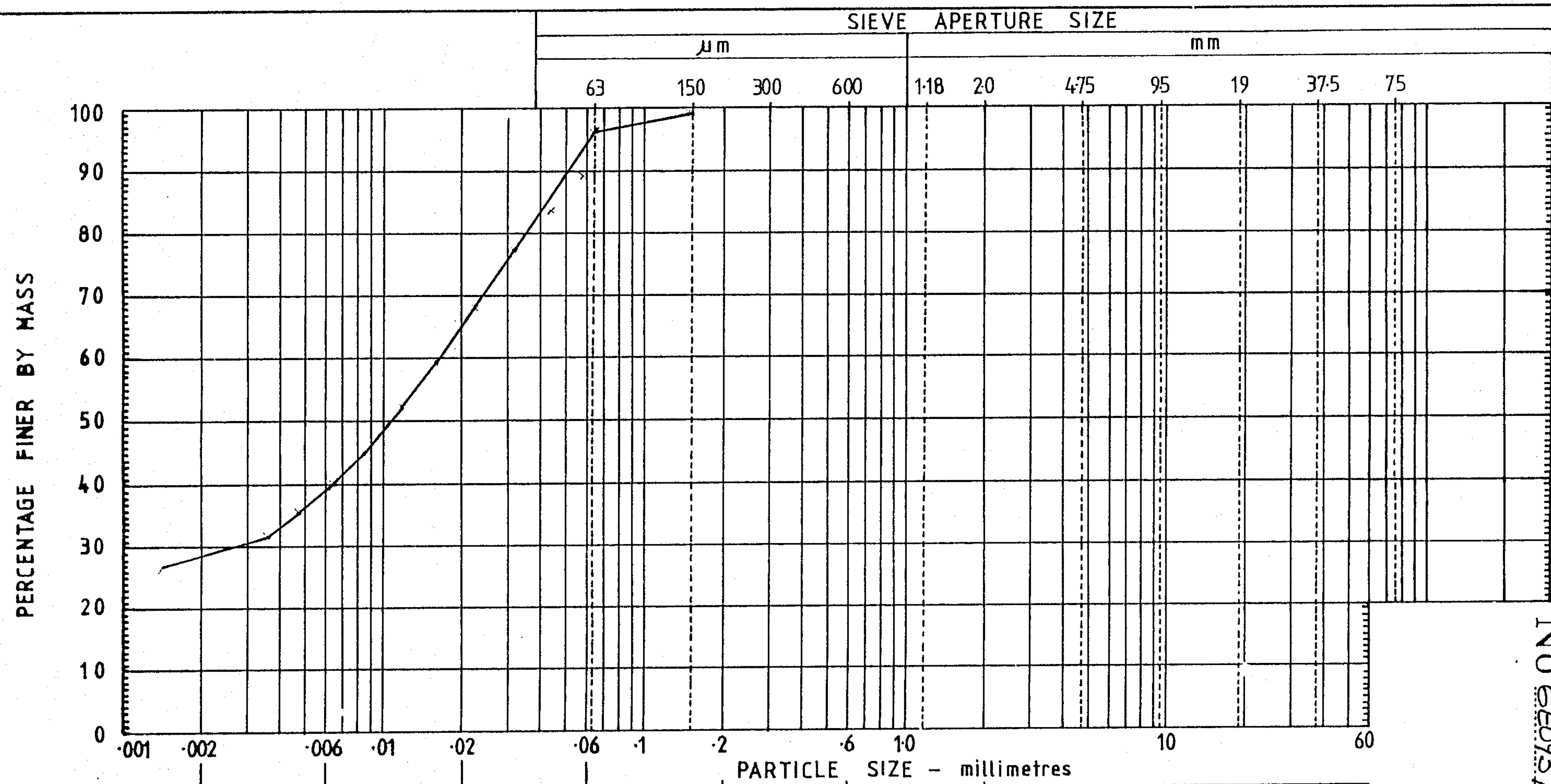
Report

No 6E093/350



SOIL FRACTIONS	CLAY	fine	medium	coarse	fine	medium	coarse	fine	coarse
		SILT			SAND			GRAVEL	

			NAME	DATE	DRAWING №.
CLIENT: WORKS WELLINGTON CONSULTANCY	SAMPLE № 2-93/4				
PROJECT: LIQUEFACTION STUDY	DEPTH. m. 10.0 -10.45	Tested by	MJM	11.1.93	
		Plotted by	MJM	14.1.93	
SOURCE: BH2 10.0 -10.45 PLIMERTON DOMAIN	WET / ~~DRY~~ SIEVE	Checked by	SW	14.1.93	

PARTICLE SIZE DISTRIBUTION

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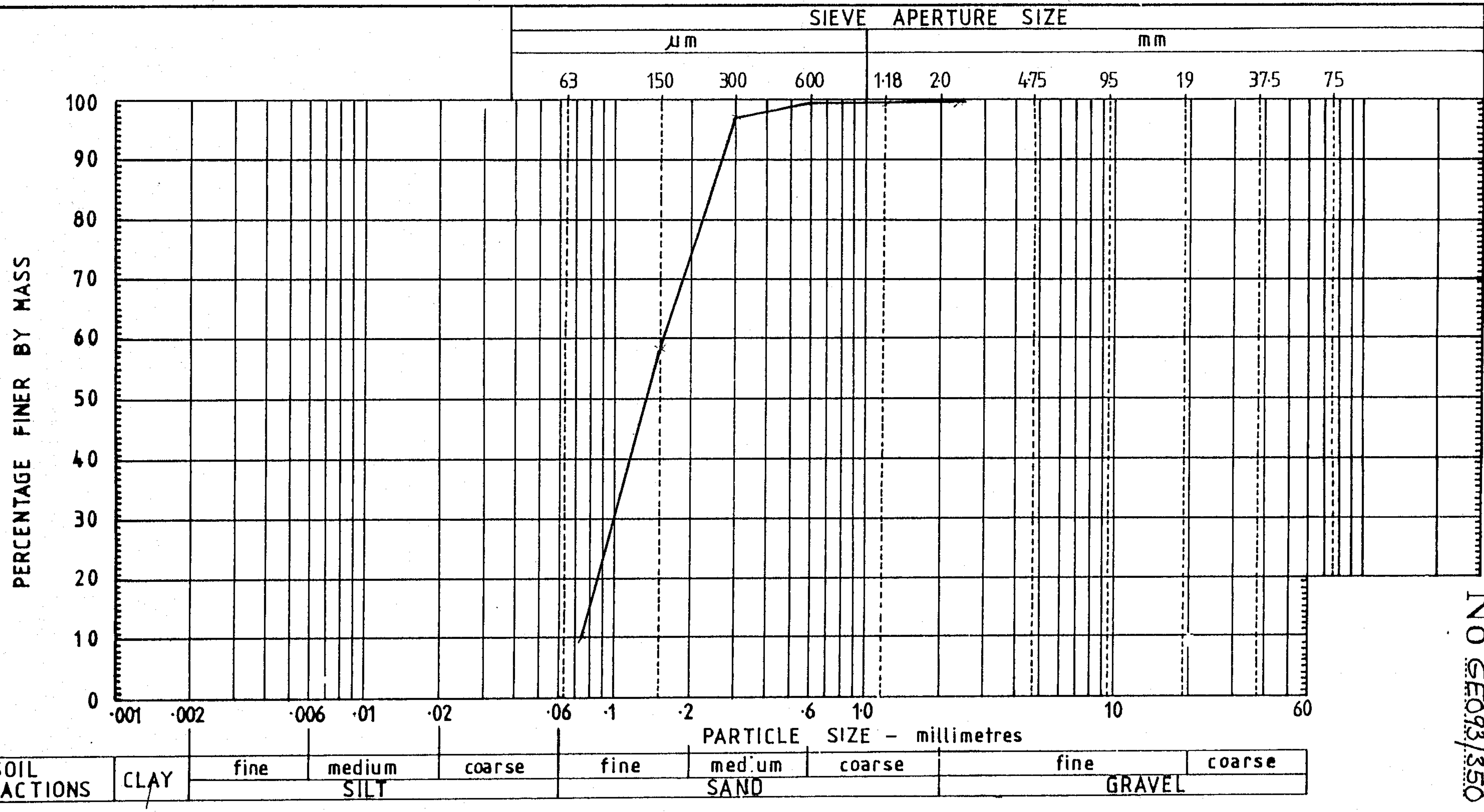
No GE093/350



CLIENT: WORKS WELLINGTON CONSULTANCY	SAMPLE Nº 2-93/1		NAME	DATE	DRAWING Nº.
PROJECT: LIQUEFACTION STUDY	DEPTH. m. 2.0m	Tested by	MJM	11.1.93	
		Plotted by	MJM	21.1.93	
SOURCE: BH1 2.0m SAMPLE A KURA PK.	WET / ~~DRY~~ SIEVE	Checked by	SW	21.1.93	

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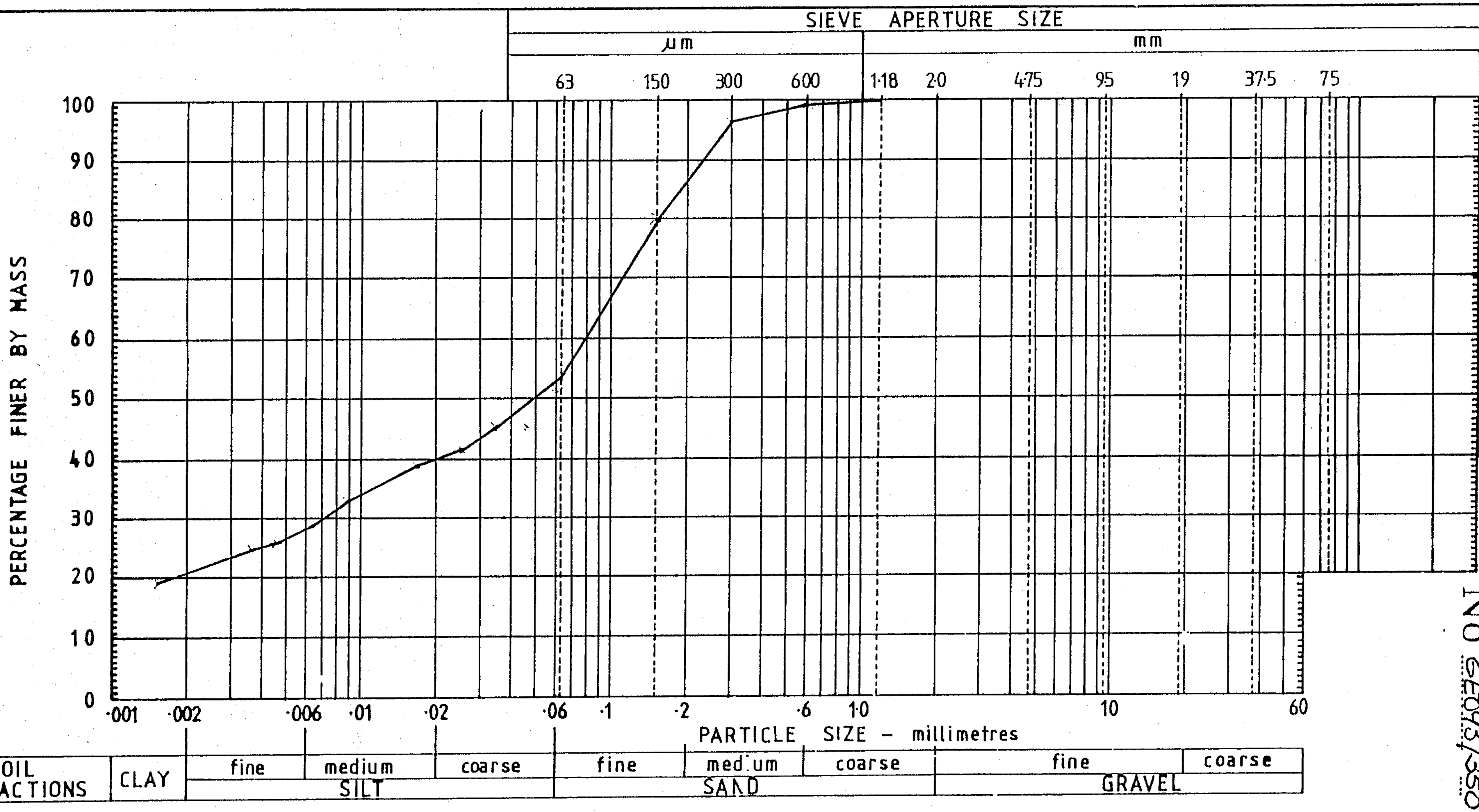
Report

No GE093/350



CLIENT: WORKS WELLINGTON CONSULTANCY	SAMPLE Nº 2-93/2		NAME	DATE	DRAWING Nº.
PROJECT: LIQUEFACTION STUDY	DEPTH. m. 7.0 – 7.15	Tested by	MJM	11.1.93	
		Plotted by	MJM	14.1.93	
SOURCE: BH 1 7.0 - 7.15m KURA PARK	WET / ~~DRY~~ SIEVE	Checked by	SW	14.1.93	

PARTICLE SIZE DISTRIBUTION

Appendix B

DEFINITION OF LIQUEFACTION TERMS

(American Society of Civil Engineers, 1978)

14037 SEPTEMBER 1978 GT9

JOURNAL OF THE GEOTECHNICAL ENGINEERING DIVISION

Definition of Terms Related to Liquefaction

By the Committee on Soil Dynamics of the Geotechnical Engineering Division

Introduction

In the past decade or so, some important variations, discrepancies, and ambiguities have developed in terminology used to describe the liquefaction phenomenon and its effects. These terminology problems have hampered communications within the geotechnical community and between technical disciplines and have allowed the possibility of misunderstandings, misinterpretations, and even misapplications. In an attempt to rectify this problem and bring unity and consistency in usage, the Geotechnical Division's Committee on Soil Dynamics has reviewed terms and definitions used in the past and prepared a suggested list of recommended definitions.

It is recognized that many engineers have strong opinions relating to definitions and terminology. Consequently, the Committee on Soil Dynamics encourages written discussion concerning the use and implication of these suggested terms and definitions. It is hoped that this document and the ensuing discussions will ultimately lead to the adaption of terms and definitions that will be used consistently in geotechnical practice and reports. Additionally, it is suggested that these definitions, after discussion and review, be added to or substituted into glossaries and lists of nomenclature and that ASCE reviewers and editors use them as a standard for ASCE publications.

The terms and definitions listed herein have received careful study and review by the Committee on Soil Dynamics and by many other individuals who responded to our open invitation to participate in the review of this document. General agreement was achieved on the definitions selected for use, although there were some dissenting opinions. Nonetheless, it is believed that these definitions provide

Note.—Discussion open until February 1, 1979. To extend the closing date one month, a written request must be filed with the Editor of Technical Publications, ASCE. This paper is part of the copyrighted Journal of the Geotechnical Engineering Division, Proceedings of the American Society of Civil Engineers, Vol. 104, No. GT9, September, 1978. Manuscript was submitted for review for possible publication on June 5, 1978.

an initial technical basis for communication and hopefully will generate further discussion within the geotechnical community that will lead to further refinements.

Definitions

Liquefaction.—The act or process of transforming any substance into a liquid (2). In cohesionless soils, the transformation is from a solid state to a liquefied state as a consequence of increased pore pressure and reduced effective stress.

Comments.—Liquefaction is thus defined as a changing of state that is independent of the initiating disturbance that could be a static, vibratory, sea wave, or shock loading, or a change in ground-water pressure. The definition also is independent of deformation or ground failure movements that might follow the transformation. Liquefaction always produces a transient loss of shear resistance but does not always produce a longer-term reduction of shear strength. The committee recommends that use be discontinued of definitions that incorporate a modifier with the term liquefaction such as "initial liquefaction," "cyclic liquefaction," "true liquefaction," etc. The tendency to subdue or drop such modifiers in routine usage has been a common source of confusion.

Related terms include the following.

Cyclic Strain Softening.—A stress-strain behavior under cyclic loading conditions in which the ratio of strains to differential shear stresses increases with each stress or strain cycle. In saturated undrained cohesionless soils cycle strain softening is caused by increased pore-water pressure.

Comments.—Continued cyclic loading usually leads to increasing axial strains and increasing pore-water pressures, but does not necessarily lead to loss of ultimate shear strength if the material is dilative.

Pore Pressure Ratio.—The ratio, expressed as a percentage, of the change of pore pressure, Δu, to either the initial effective minor principal stress, $\bar{\sigma}_{3c}$, at the end of primary consolidation (normally used in cyclic triaxial compression tests) or the vertical effective overburden pressure, $\bar{\sigma}_v$ (normally used in simple shear tests and in field studies). The reporter must specify which ratio is being used.

Peak Pore Pressure Ratio.—The maximum pore pressure ratio measured during a particular loading sequence.

Full or 100% Pore Pressure Ratio.—A condition in which Δu equals $\bar{\sigma}_{3c}$ or $\bar{\sigma}_v$ as the case may be.

Comments.—In many contexts this term replaces the ambiguous term "initial liquefaction" which was used by some geotechnical engineers in the past.

Shear Strength.—The maximum resistance of soil or rock to shearing stresses (3).

Related terms include the following.

Cyclic Shear Resistance.—The level of cyclic stress required to produce liquefaction or a given amount of strain in a specified number of loading cycles.

Comment.—This term replaces the term "cyclic shear strength."

Normal Strain.—The change of length per unit length in a given direction (3).

Shear Strain.—The change in shape, expressed by the relative change of the right angles at the corner of what was in the undeformed state an infinitesimally small rectangle or cube (3).

Comments on Normal and Shear Strain.—These are general strain terms that can be applied to deformations in cohesionless soils either in the solid or liquefied states. They may be expressed either in terms of a dimensionless ratio or as a percentage. The reporter must specify which form is being used.

Related terms include the following.

Peak Strain.—The maximum or minimum strain (from the origin or initial state) produced during a particular loading sequence.

Comment.—In cyclically loaded triaxial tests the peak compressional axial (normal) strain is usually reported; however, if the peak extensional axial strain is larger than the peak compressional axial strain both axial strains should be reported. The peak strain thus includes accumulated extensional or compressional strains accrued during a test.

Peak to Peak Strain.—The difference between the maximum and the minimum normal or shear strain during a given cycle under cyclic loading conditions.

Comment.—Under cyclic loading conditions it is often more convenient or more pertinent to report peak to peak strain than peak strain. If the peak strains are not symmetrical for symmetrically loaded tests, then the peak compressional normal strain or positive shear strain should be given along with the peak to peak strain.

Limited Flow Strain or Limited Flow Deformation.—Flow strains or deformations that commence following liquefaction but are arrested after a finite displacement, usually as a consequence of a dilantancy caused pore pressure drop and accompanying increase of effective stress. These deformations are accompanied by transient loss of shear resistance rather than permanent loss of shear strength.

Unlimited Flow Strain or Unlimited Flow Deformation.—Flow strains or deformations that commence following liquefaction and continue unabated under undrained constant total stress conditions. These deformations are accompanied by permanent loss of shear strength.

Comment.—This behavior has been called "true liquefaction" by some engineers in the past.

Ground Failure.—A permanent differential ground movement capable of damaging or seriously endangering a structure.

Comment.—This term and the following related terms are applicable to field behavior.

Related terms include the following.

Lateral Spread.—Distributed lateral extensional movements in a fractured mass in which extension of a rock or soil results from liquefaction or plastic flow of subjacent materials (4).

Flow Failure.—A form of slope movement involving the transport of earth materials in a fluid-like manner over relatively long distances, at least several tens of feet.

Sand Boil.—An ejection of sand and water caused by piping from a zone of excess pore pressure within a soil mass.

Comments.—Sand boils commonly form during or immediately after earthquakes as pressures are relieved from liquefied or other zones or excess pore pressures in subsurface saturated cohesionless soils. The term sand boil is preferred to sand blow because the latter is used to describe other phenomena such as the denudation of a local area by wind action (1).

ACKNOWLEDGMENT

This report is respectfully submitted by the Committee on Soil Dynamics of the Geotechnical Engineering Division.

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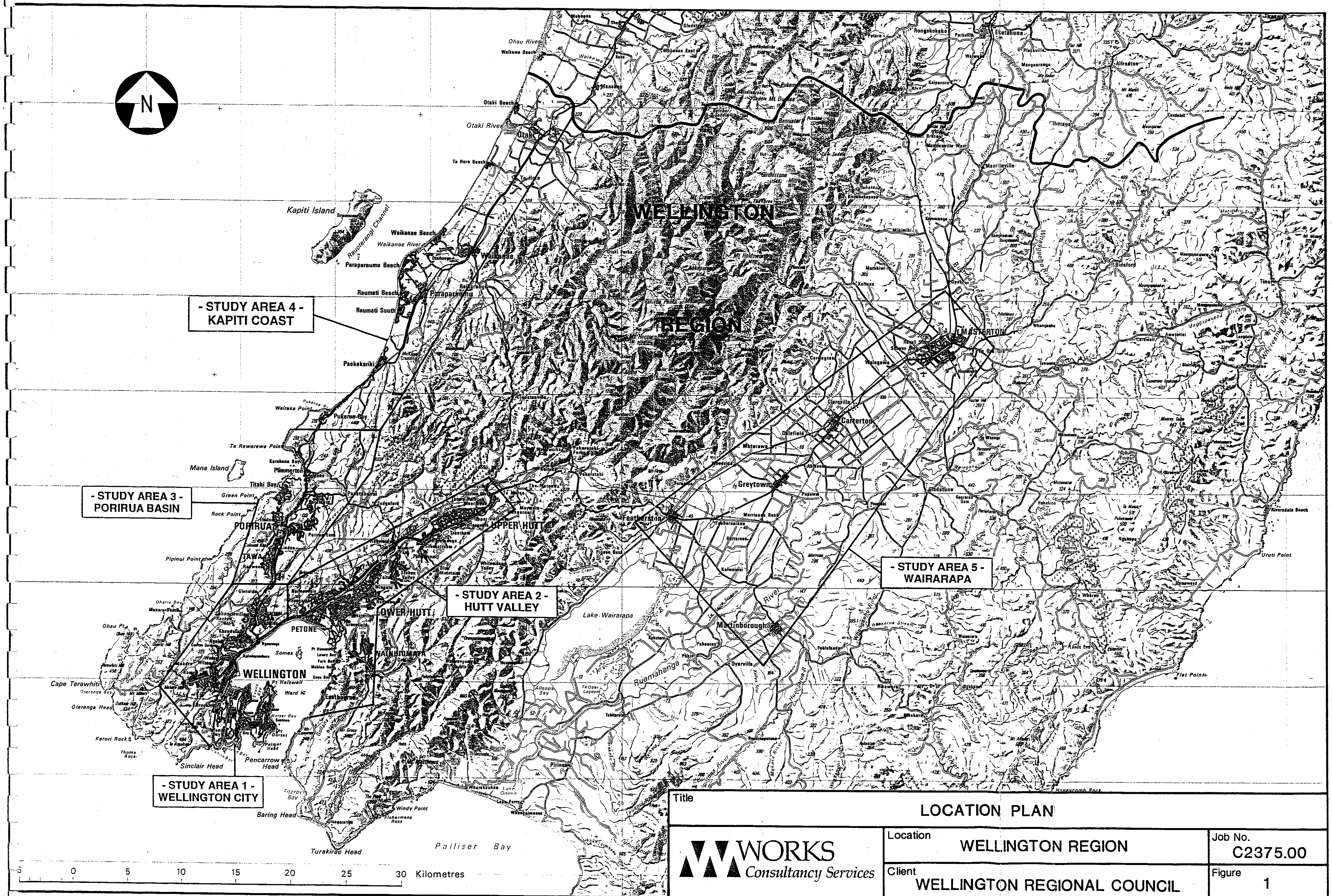
Richard N. Hwang	Ray N. Yong
Izzat M. Idriss	T. Leslie Youd
John Lysmer	William F. Marcuson III, Chairman
John P. Mulilis	

APPENDIX.—REFERENCES

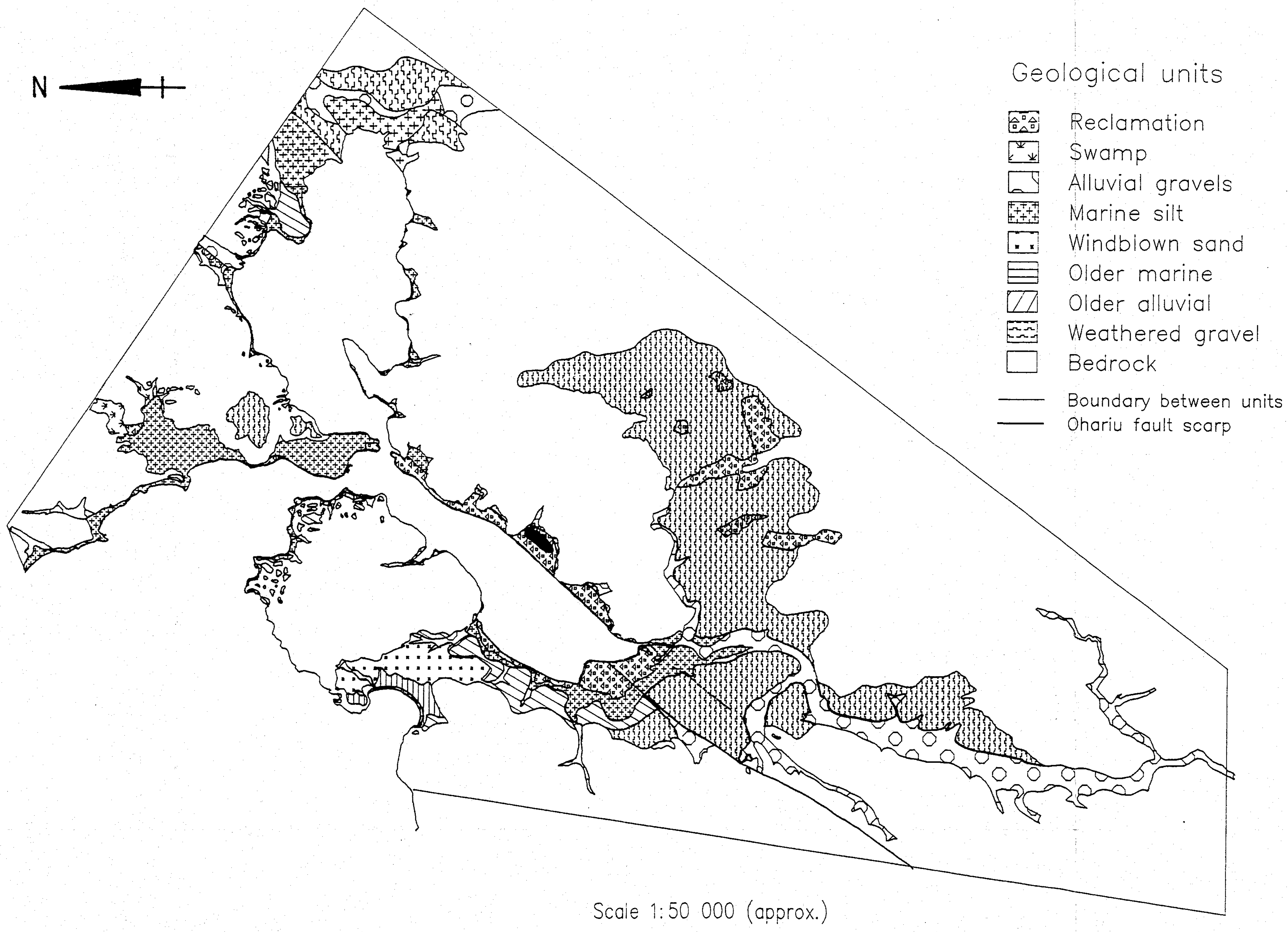
1. Gary, M., McAfee, R., Jr., and Wolf, C. L., eds., *Glossary of Geology*, American Geological Institute, Washington, D.C., 1972.
2. Lange, N. A., and Forker, B. S., eds., *Hankbook of Chemistry*, 10th ed., McGraw-Hill Book Co., Inc., New York, N.Y., 1967.
3. "Standard Definitions of Terms and Symbols Relating to Soil and Rock Mechanics," Standard D653, in *1978 Annual Book or Standards, Part 19*, American Society for Testing and Materials, Philadelphia, Pa., 1978, pp. 120–137 (in press).
4. Varnes, D. J., "Slope Movement Types and Processes," *Landslides: Analyses and Control, Transportation on Research Board*, Special Report 176 (in press).



Title
LOCATION PLAN

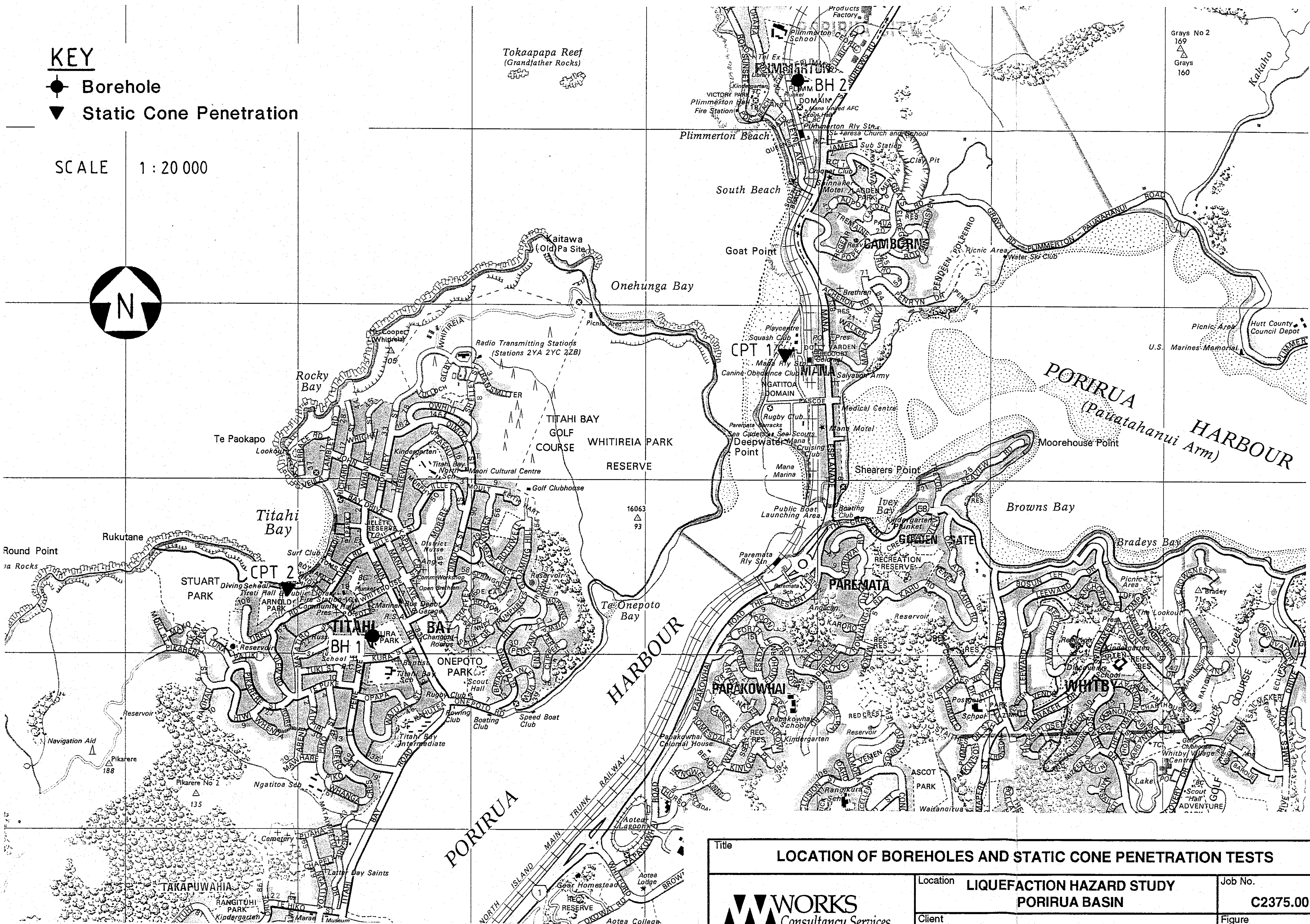
WORKS Consultancy Services

Location	Job No.
WELLINGTON REGION	C2375.00
Client	**Figure**
WELLINGTON REGIONAL COUNCIL	1

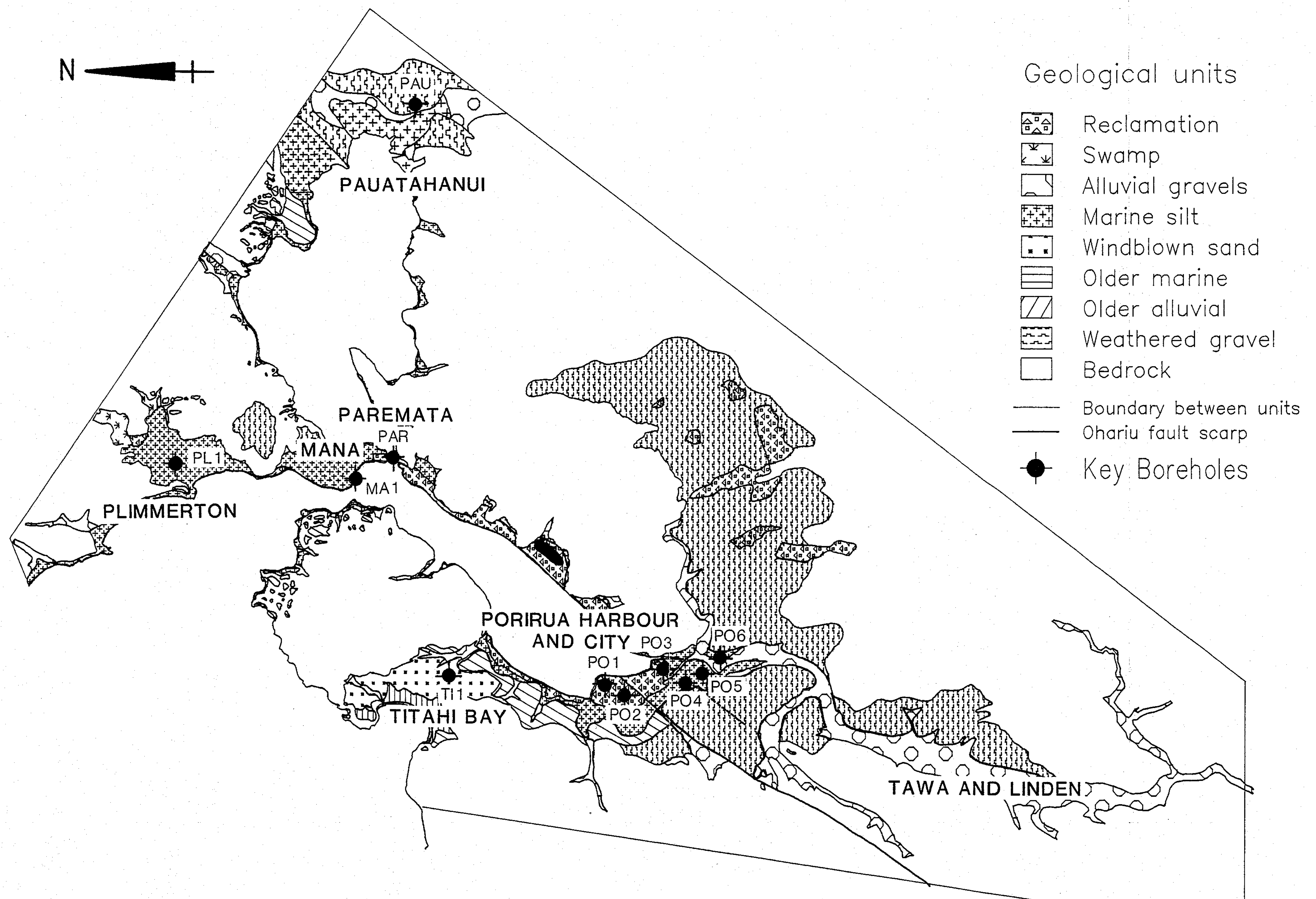


After Dellow et al (1992)

Title		
SURFACE GEOLOGICAL MAP OF PORIRUA BASIN		
WORKS Consultancy Services	Location: LIQUEFACTION HAZARD STUDY PORIRUA BASIN	Job No. C2375.00
	Client: WELLINGTON REGIONAL COUNCIL	Figure 2



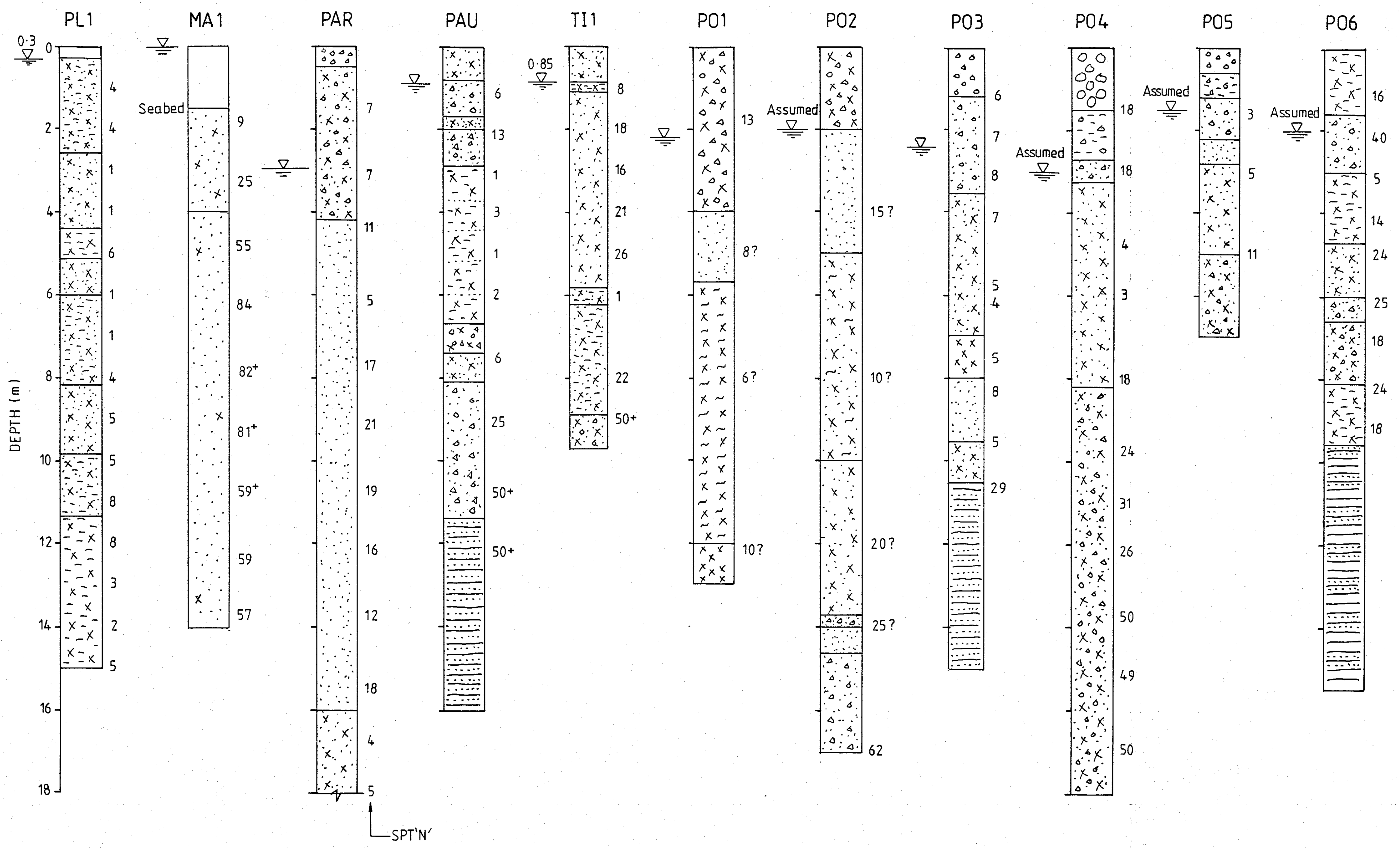
Title	LOCATION OF BOREHOLES AND STATIC CONE PENETRATION TESTS	
WORKS Consultancy Services	Location: LIQUEFACTION HAZARD STUDY PORIRUA BASIN	Job No. C2375.00
	Client: WELLINGTON REGIONAL COUNCIL	Figure 3



Scale 1:50 000 (approx.)

After Dellow et al (1992)

Title	LOCATION OF KEY BOREHOLES FOR LIQUEFACTION ASSESSMENT		
WORKS Consultancy Services	Location: LIQUEFACTION HAZARD STUDY PORIRUA BASIN	Job No. C2375.00	
	Client: WELLINGTON REGIONAL COUNCIL	Figure 4	

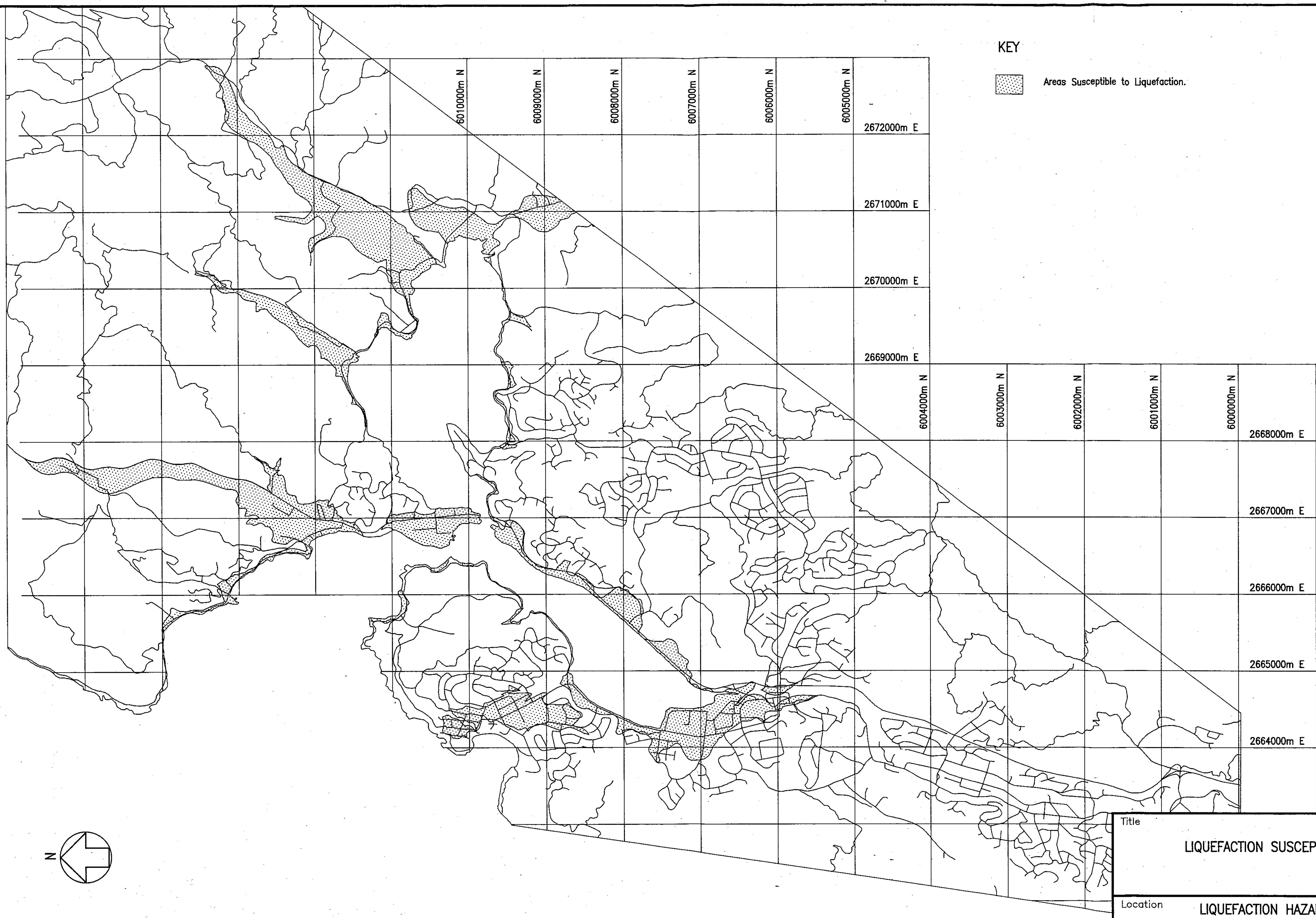


KEY

GWL	
SPT'N'	Standard Penetration Test 'N'
Clay	Rockfill
Silt	Sandstone
Sand	Organic Material
Gravel	Mudstone

Note: See Figure 4 for location of Key Boreholes.

Title	**SUMMARY LOGS OF KEY BOREHOLES**	
WORKS Consultancy Services	Location: **LIQUEFACTION HAZARD STUDY PORIRUA BASIN**	Job No. C2375.00
	Client: **WELLINGTON REGIONAL COUNCIL**	Figure 5



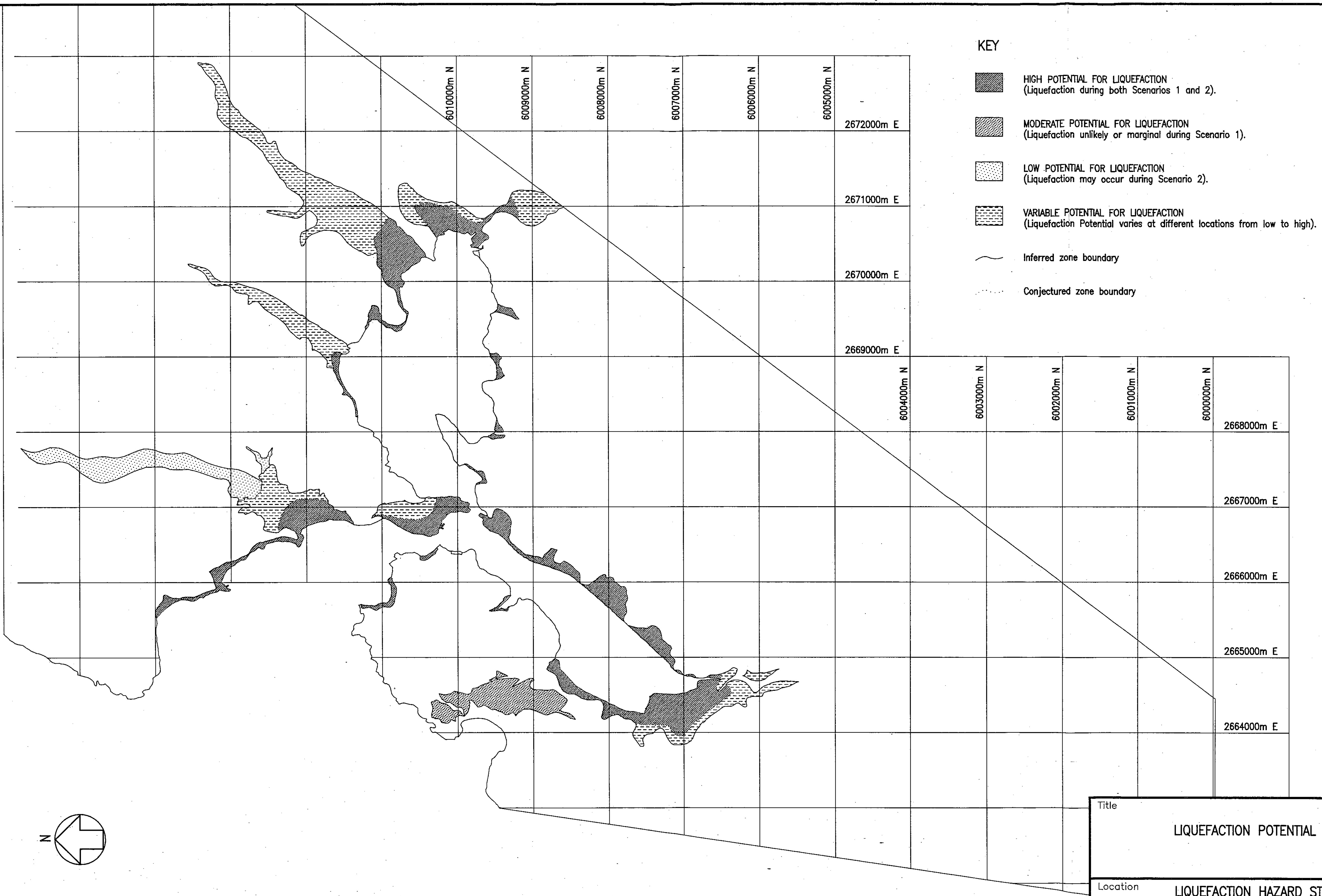
KEY

Areas Susceptible to Liquefaction.

NOTE This map should be read in conjunction with the report "Liquefaction Hazard Study, Wellington Region: Study Area 3 – Porirua Basin" (Works Consultancy Services, 1993).

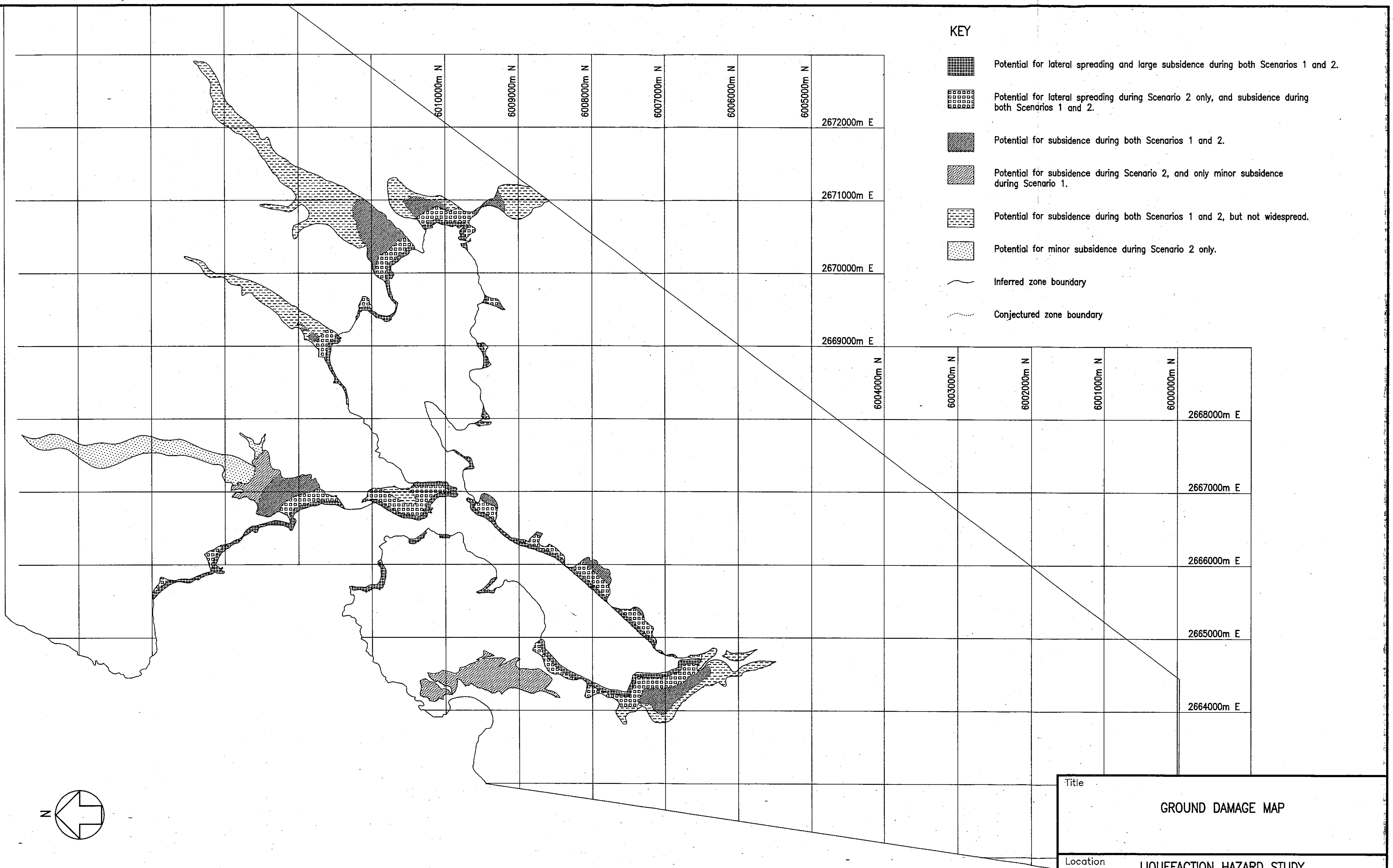
1:25000 0 0.5 1 1.5 2 km

Title	LIQUEFACTION SUSCEPTIBILITY MAP
Location	LIQUEFACTION HAZARD STUDY PORIRUA BASIN
Client	WELLINGTON REGIONAL COUNCIL
WORKS Consultancy Services	Job No. C2375.00
	Figure 10



NOTE This map should be read in conjunction with the report "Liquefaction Hazard Study, Wellington Region: Study Area 3 – Porirua Basin" (Works Consultancy Services, 1993).

Title	LIQUEFACTION POTENTIAL MAP
Location	LIQUEFACTION HAZARD STUDY PORIRUA BASIN
Client	WELLINGTON REGIONAL COUNCIL
WORKS Consultancy Services	Job No. C2375.00 Figure 11



NOTE This map should be read in conjunction with the report "Liquefaction Hazard Study, Wellington Region: Study Area 3 – Porirua Basin" (Works Consultancy Services, 1993).

Title	GROUND DAMAGE MAP
Location	LIQUEFACTION HAZARD STUDY PORIRUA BASIN
Client	WELLINGTON REGIONAL COUNCIL
WORKS Consultancy Services	Job No. C2375.00
	Figure 12